

Component Development for a Microchannel *In Situ* Propellant Production System

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Abstract

Pacific Northwest National Laboratory is using microchemical/thermal systems (MicroCATS) to develop a Mars-based *In Situ* Propellant Production system. This system will collect CO₂ from the Martian atmosphere, react it with hydrogen gas carried from earth, and separate individual components, recovering water and producing fuel (CH₄) and oxidizer (O₂) for the return voyage. Development is underway on three primary sub-systems: a thermochemical compressor, catalytic reactors, and components for separating gas phases from liquid phases. The thermochemical compressor currently under development for laboratory testing is designed to achieve a 10x compression of CO₂, increasing the CO₂ partial pressure from ~10 kPa to ~100 kPa, using temperature swing adsorption. The higher compression ratio to collect Martian atmospheric CO₂ at ~0.8 kPa and compress it to at least 100 kPa can be achieved with two adsorption stages in series. A compressor stage incorporates eight thermally coupled adsorption cells at various stages in the adsorption/desorption cycle to maximize the recuperation of thermal energy and provide a nearly continuous flow of CO₂ to the downstream reactors. The thermochemically compressed CO₂ will be mixed with hydrogen gas and fed to two reactors: a Sabatier Reaction unit and a Reverse Water/Gas Shift unit. The microchannel architecture allows heat addition and removal, resulting in significantly higher conversion than possible with an adiabatic system. By operating these reactors at the proper flowrates, in combination with a water electrolysis unit, a specified ratio of CH₄ and O₂ product can be obtained. A microchannel phase separator is also under development to separate liquid water from vapor and other gases in these product streams. This phase separator relies on surface forces, not gravitational effects, to separate the water and is therefore suited to space applications. Data collected during the design and development of these unit operations will be discussed.

Introduction

An *in situ* propellant production (ISPP) plant on future Mars robotic missions can produce oxygen (O₂) and methane (CH₄) that can be used for propellant for the return voyage. Specific system analyses of robotic and human Mars missions show that producing propellants from Mars atmospheric carbon dioxide (CO₂) and hydrogen (H₂) brought from Earth can reduce the initial mass launched in low Earth orbit by 20% to 45%, as compared to carrying all of the propellant for a round-trip mission to the Mars surface from Earth. The primary resource initially under consideration for future Mars missions is its low pressure (0.8 kPa), low temperature (184 to 242 K) atmosphere, which consists of mostly carbon dioxide (95.5%), nitrogen (2.7%), and argon (1.6%), with traces of other gases (0.15% oxygen; <0.03% water) (Kaplan 1988). To minimize mission risk, the ISPP system must be compact and highly efficient chemically, thermally, and electrically to minimize the mass of the propellant production plant, power system, and H₂ brought from Earth. To attain the goals, Pacific Northwest National Laboratory (PNNL) and the NASA Johnson Space Center are investigating the use of Micro Chemical/Thermal System (MicroCATS) technology toward the development of an O₂/CH₄ propellant production plant on Mars.

Research has been performed to develop microchemical processes for some of the major components of this system. Among those studied are the CO₂ compression subsystem using adsorption, the reactor subsystem using Sabatier reaction (SR) and Reverse Water Gas Shift (RWGS) reactions, and a vapor/liquid separation subsystem using wicking in a microchannel. This work will be discussed further in subsequent sections. System sizing is based on NASA's robotic sample return mission that requires production rates of 0.0977 kg/hr of methane and 0.371 kg/hr of oxygen.

CO₂ Collection and Compression Subsystem

Selective sorbents, whether liquid absorbents or solid adsorbents, tend to have a higher capacity for the target adsorbate species (e.g., CO₂) when cool than when hot. Therefore, thermal cycles in which the sorbent is cooled during adsorption and heated during desorption are a means to capture CO₂ from Mars at a low partial pressure (~0.8 kPa) and subsequently release it in a much more concentrated form (100 kPa) for downstream processing in ISPP reactors. This is a thermal-swing adsorption (TSA) thermochemical compression process. The production rate of CO₂ (e.g., 0.8 kg/hr required for a Mars robotic sample return) is a function of the amount of sorbent in the system, the difference in sorbent capacity for adsorbate in a cooled highly loaded state and a heated minimally-loaded state, and the frequency of cycling between these two end states. By cycling rapidly to achieve continual CO₂ delivery and sorbent regeneration, the specific productivity of the sorbent ([kg-CO₂/s]/kg-sorbent) is increased over a more conventional long-cycle process (e.g., a Mars diurnal cycle). For a given CO₂ throughput, the mass of adsorbent material required is proportional to the cycle time. Micro-scale adsorbers and absorbers are ideally suited to rapid thermal cycles, and as a result, the mass of sorbent and the device hardware for the Mars mission are reduced.

The development of an adsorption-based CO₂ thermochemical compressor started with single-channel devices, which were readily fabricated and tested in the laboratory. Subsequently, concepts for much more complex multi-channel and multi-cell adsorbers were developed. We discuss below the design of a multi-cell adsorber that we are preparing to fabricate for future testing and its basis in single-channel test units.

Development and Testing of a Single-Channel Adsorber

Several compact single-channel adsorbers were fabricated and tested to demonstrate proof-of-concept for CO₂ capture and subsequent delivery in rapid adsorption/desorption cycles (Rassat et al. 2001). As a result of integrating the heat-exchange microchannels on both sides of a single mesochannel-filled adsorbent bed, the devices are well suited to a TSA process. Heat-exchange fluid was delivered to and received from the heat-exchange microchannels using a common header/footer system, while an independent header/footer system was used to deliver and collect adsorbate gas species to and from the sorbent. A thin solid heat-transfer surface isolated the heat-exchange fluid from the adsorbent bed and resulted in heat-transfer to or from the adjacent layer of adsorbent. These single-adsorbent channel test units were “flow through” type adsorbers in which the adsorbate and carrier gas flowed through the interstices of the adsorbent bed.

The following is an example typical of experiments completed with single-channel adsorbers. The tests were isobaric (atmospheric pressure, ~100 kPa) and operated in a two-phase TSA cycle. A stainless steel unit containing 1.2-g zeolite 13X was cycled with a minimum measured adsorption temperature T_l of 12 °C and a maximum desorption temperature T_h of 77 °C using water as a heat-exchange fluid. Pure CO₂ was fed through the zeolite at the rate of ~50 mL/min during a ~60-s adsorption phase in which the adsorbent was cooled from T_h to T_l . The desorption phase, including the time to heat from T_l to T_h , was also ~60 s, resulting in an overall cycle time of 2 min. During the heating portion of the cycle, about 46 mL of CO₂ (measured at room temperature, ~22 °C) corresponding to 0.084-g CO₂ was desorbed. The theoretical working capacity for these conditions, as determined from vendor-supplied adsorption isotherms and isobars, is 0.090 g of CO₂. Therefore, 93% of the theoretical working capacity was measured experimentally. The less than maximum working capacity for the device is thought to be due to partial water “poisoning” of the adsorbent. Water is strongly adsorbed on zeolite 13X, and the adsorption device was not heated sufficiently to remove all water before the CO₂ experiment. Nonetheless, this type of experiment demonstrated our ability to cycle rapidly and to effectively utilize the sorbent capacity. It also gave confidence in the use of standard adsorption isotherms as a baseline for comparison to experimental data and for modeling activities supporting follow-on designs.

Multi-Channel, Multi-Cell Adsorber

The isobaric adsorption process noted above is akin to a purification scheme where the adsorbate gas is stripped from the feed stream to purify it, and subsequently the adsorbed species are exhausted at the same pressure to some reservoir (e.g., earth atmosphere). For the Mars mission, the need is to increase the CO₂ partial pressure about 125-times above its Mars atmospheric level and provide this stream at an appropriate rate for producing propellants. These goals can be met with multi-channel and multi-cell adsorption thermochemical compressors that we are currently developing.

We defined the adsorbers above as “single-channel” devices because they contained only one adsorbent-filled layer. To increase the capacity of the thermochemical compressor to produce CO₂ while maintaining rapid cycling capability, multiple adsorbent-filled channels effectively coupled with heat-transfer surfaces are needed. Figure 1 depicts, in cross section, one fabrication scheme for a multi-channel adsorber. The figure shows two adsorbent mesochannels, each adjacent to one heat-exchange fluid microchannel. There is also a gas flow microchannel placed between the two adsorbent layers. In this approach, adsorbate species are transported by diffusive mass transport to or from the adsorption sites in the adsorbent layers through porous contactors, which separate the adsorbent from the gas flow channel. During adsorption, for example, a gas stream containing adsorbate species is pumped through the gas flow channel (normal to the plane of the figure) and adsorbate species diffuse (substantially in the plane of the figure) to the adsorption sites. This adsorption scheme is “flow-by” instead of the flow-through approach described for the single-channel adsorbers. In the Mars application, we are particularly sensitive to pressure drop when feeding gas to the device from the Martian atmosphere. This flow-by mesochannel adsorber system is designed to minimize pressure drop while still providing rapid adsorbate mass transfer.

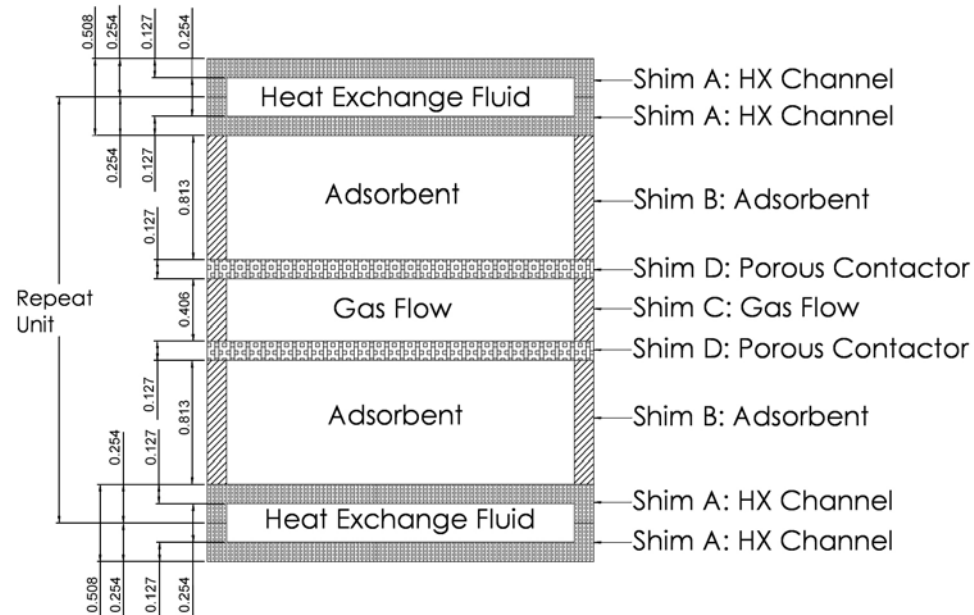


Figure 1. An arrangement of four unique shim types defines heat-exchange fluid, gas flow, and adsorbent channels within a single repeat unit of a flow-by adsorber. Dimensions in Millimeters.

The channels of Figure 2 are defined by a specific arrangement of four unique laminates or shims: a pair of shims (A) establishes a heat-exchange microchannel; each Shim B creates an adsorbent mesochannel; Shim C provides the gas-flow channel; and each Shim D is a porous contactor allowing diffusive mass transport between the adsorbent and gas-flow channels. Seven shims, two each of A, B, and D and one of C, create a repeat unit. Figure 2 shows the four shim designs for an eight-cell flow-by adsorber of octagonal symmetry in plan view. (Some details of the heat-exchange and porous contactor shims [A and D] are not completely represented in the figure.) The two triangular cutouts within each of the trapezoidal octants of the shims form the heat-exchange fluid header and footer for the cell.

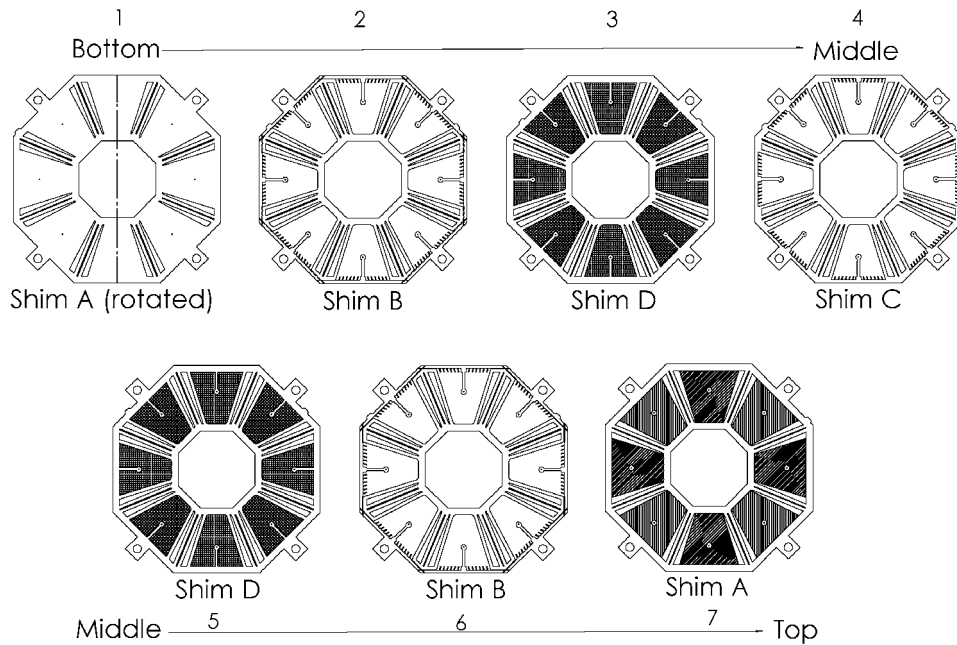


Figure 2. Plan view of shims in a repeat unit demonstrating the octagonal symmetry of an eight-cell adsorber.

Stacking multiple repeat units vertically increases the number of adsorbent channels and the adsorbent volume in an adsorption cell with no penalty in heat and mass-transport efficiency. Figure 3 shows the stacking arrangement for an eight-cell adsorber consisting of twelve repeat units. Perhaps more obvious with reference to Figure 1, one extra heat-exchange channel is needed at each end of the repeat unit stack to cap the terminal heat-exchange channels. End plates shown in Figure 3 are beneficial in the diffusion bonding process and are ultimately used for external header and footer connections for the heat-exchange fluid. After bonding and some machining, the structure of Figure 3 is converted to the eight-cell adsorber shown in Figure 4. Removal of a significant fraction of the material from the end plates after bonding serves two functions: first, it reduces the device mass, and second, it reduces the potential duty of heating and cooling of that mass during thermal cycles. The latter is especially important if the endplate material is thermally conductive and has a large heat capacity. To further minimize the “thermal mass” of the adsorber and to maintain the ruggedness provided by bonded metal necessary for space travel, we plan to fabricate and test an adsorber like Figure 4 in titanium. Titanium has roughly half the density and about half the heat capacity on a volume basis of stainless steel.

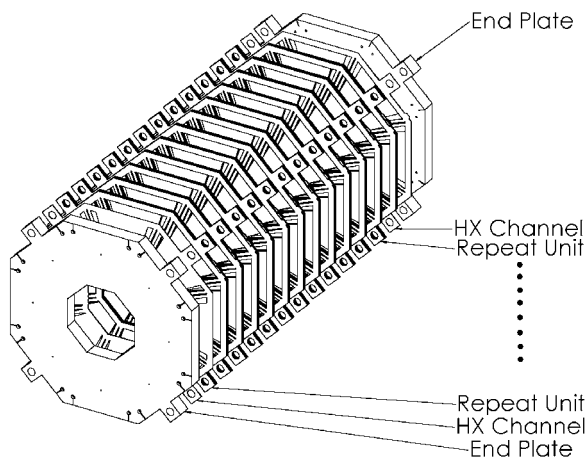


Figure 3. An exploded view of multiple repeat units, capping heat-exchange shims, and endplates arranged for bonding.

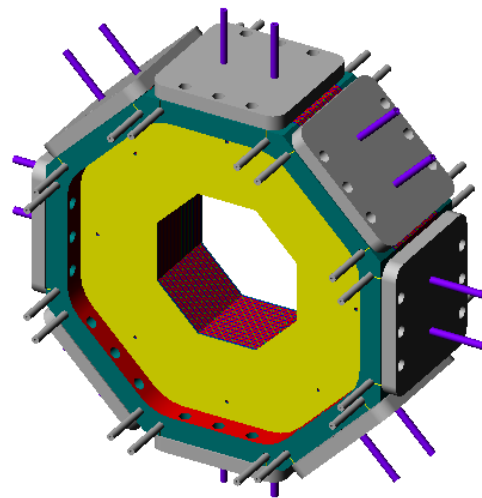


Figure 4. A completed adsorber with tube stubs for external adsorbate gas and heat-exchange fluid connections.

A prime advantage of a multi-cell adsorber is its capability to provide a semi-continuous stream of CO₂ by adsorbing in some cells at the same time others, which were previously loaded, are desorbed. The energy penalty associated with thermal cycling of the cells from cold to hot to cold... is minimized if the mass of structure other than the adsorbent that is cooled and heated is reduced or if thermal energy is effectively recuperated from cycle to cycle. We are pursuing both in units such as that shown in Figure 4. By proper linking and control of the heat-exchange fluid streams, hot fluid from desorption cells is fed to fully loaded adsorption cells to start the desorption process. Simultaneously, the cold heat-exchange fluid stream from the fully CO₂-loaded adsorber is directed to desorption cells, which were previously heated to purge adsorbate, to prepare for another adsorption cycle. The amount of heat that must be added to the desorber and removed from the adsorber from external sources is a function of the thermal recuperation efficiency and the heats of sorption. Since adsorption is typically exothermic and desorption is endothermic, energy must be removed or added from the adsorbent to affect the sorption cycle. These heats of sorption are the minimum thermodynamic energy cost to compress gas thermochemically.

Figure 4 is a model of the laboratory-scale CO₂ thermochemical compressor being developed for the NASA ISPP project. The plates on each of the eight cells are the header/footer ports for the fluid stream containing the adsorbate gas. In the case of collecting and compressing CO₂ on Mars, Martian atmospheric gas is introduced into the cooled adsorption cell(s) through these ports. After isolating cells from the Martian atmosphere, the cells are heated, gas is desorbed from the adsorbent, and the CO₂ partial pressure within the gas phase of the sealed cells increases. When the temperature nears or is at the maximum desorption operating temperature for the system, the ports on the desorption cell(s) are opened to provide compressed CO₂ to the microchannel reactors for propellant production. Using computational models, we scaled the unit shown in Figures 3 and 4 to produce ~0.1 kg-CO₂/hr using commercially available zeolite 13x with minimum adsorption and maximum desorption operating temperatures of 0 and 100°C. The CO₂ production rate is one-eighth that required for a Mars robotic sample return mission. The production capacity of the system can be increased with more adsorbent mass (more channels) per cell, larger temperature swings, and/or more rapid cycles.

Additionally, the target CO₂ compression ratio of 10x for the laboratory system is only ~one-twelfth that needed to compress CO₂ on the Martian atmosphere at 0.8 kPa to the 100 kPa required for CH₄ propellant production. Two strategies are proposed to increase the CO₂ compression ratio for a Mars mission using our adsorption thermochemical compressors. All else being constant, expanding the temperature difference between adsorption and desorption will typically increase the compression ratio. Operating multiple sorption thermochemical compressor stages in series, each stage a multi-cell adsorber such as Figure 4 is another means to increase the compression ratio for a fixed temperature range. Our model results indicate, as expected, that operating a large number of stages in series reduces the overall amount of adsorbent needed to produce a compressed adsorbate stream at a specified rate and compression ratio. Practical considerations such as hardware complexity and mass limit the number of beneficial stages to small finite numbers. Currently, a two-stage mesochannel adsorption thermochemical compressor system appears optimized to produce CO₂ for the Mars robotic sample return mission.

CO₂ Reaction Subsystem

To produce O₂ and CH₄ at the mass ratio required for efficient propulsion-system operation (>3:1), a system that combines the SR Reaction, RWGS Reaction, and Water Electrolysis (WE) processes was selected. The system operates as follows. The CO₂ is combined with Earth-supplied H₂ and then catalytically reacted to form CH₄ and H₂O in the exothermic (ΔH=-165 kJ/mol) and self-sustaining SR. The H₂O vapor produced is condensed and decomposed in the WE process into H₂, which is recycled back to the SR, and O₂. Since the combined SR/WE process produces O₂ and CH₄ at only a 2:1 mass ratio, the RWGS reaction is required to make more oxygen. The RWGS reaction produces H₂O and CO by combining CO₂ and H₂ in an endothermic, non-equilibrium catalytic reaction (ΔH=+37.2 kJ/mole). The H₂O is again condensed and decomposed in the WE process as before, and the CO is separated and discarded.

As with all the subsystems in the ISPP, minimizing the size and weight of the reactors is essential. Maximizing the activity of catalyst and obtaining high CO₂ conversion can accomplish this. High CO₂ conversion is only possible by controlling the temperature. Since the SR is exothermic, and the RWGS is endothermic, under adiabatic conditions, as the reaction progresses, the SR reaction temperature rises and the RWGS reaction temperature falls. In both cases, thermodynamic equilibrium conversion is reduced. Using MicroCATS architecture, the temperature of these reactions can be controlled to improve conversion and the resultant reactor sizing.

RWGS Reaction System Design

The RWGS reactor was designed based on single channel tests to be one half scale for a sample return robotic mission to Mars. The overall dimensions of this half-scale reactor are 3.5 x 3.5 x 6 cm. The reactor is shown in Figure 5. Because the RWGS reaction is endothermic and strongly limited by equilibrium, the key to high conversions is to provide a means of heating the reactants to their required temperature and then maintaining this temperature during operation. To do this, four sets of 30 microchannels each were used. Each set of microchannels had three electric rod heaters on either side evenly spaced down the length of the reactor to maintain temperature. Since each of these sets of microchannels is symmetric, only one of them was tested during these operations.

Before entering the microchannels, the feed gases passed through a recuperative heat exchanger. There is one recuperative heat exchanger for each set of 30 microchannels. The recuperative heat exchanger preheats the RWGS feed streams with the product streams with an effectiveness of ~0.88. The feed gases then pass through a heating channel within the reactor block to bring their temperature up to the required inlet temperature. The gases are then distributed into the microchannels containing the Battelle-proprietary catalyst. The gases are then cooled to sub-ambient with a chiller and microchannel condenser to remove the water before they are measured with a gas chromatograph with a thermal-conductivity detector.

The reaction temperature is measured with a thermocouple based on the product gas-temperature outlet. The temperature of the gases passing through the heating channel within the reactor block were also measured and found to be within 10°C of the product gases. No temperature measurements were made in the microchannels themselves. The operating pressure of the reactor ranged from 130 to 180 kPa, which is approximately the pressure obtained from thermochemical compression of the CO₂. During the system optimization, the system pressure may be reduced to decrease the required CO₂ compression and subsequent size of the adsorption subsystem.

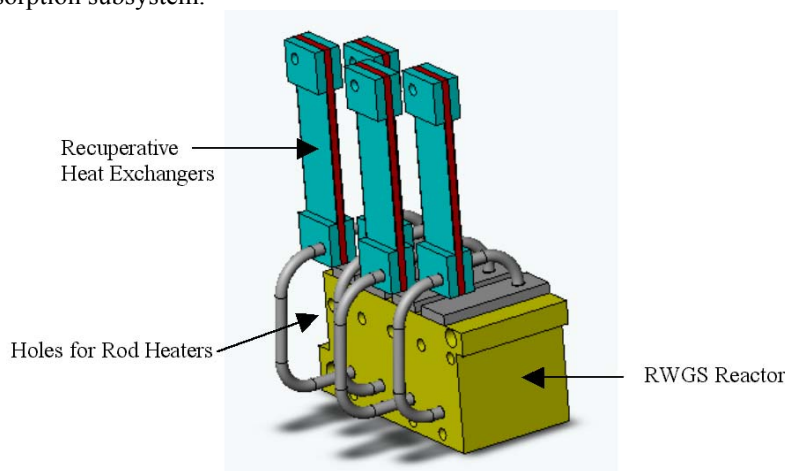


Figure 5. Drawing of the ½-scale RWGS reactor and four recuperative heat exchangers.

The system described above was used to obtain RWGS CO₂ conversion and CO selectivity data over a range of temperatures, and reactor contact times¹. Figure 6 illustrates CO₂ conversion as a function of temperature and contact time. As would be expected, the conversion increases with temperature and decreases with contact time. At the design condition of 36-ms contact time, the reactor outlet reached equilibrium conditions. By doubling the flowrate (to 18-ms contact time), the overall reactor is large enough to support the entire sample return mission, but there is a slight decrease in conversion.

Due to thermodynamic equilibrium, the conversions are constrained to fairly low levels. One approach that was tested successfully to improve conversion is to use two stages of RWGS reactions with a water-separation step between. By removing the water after the first stage of the reaction, the equilibrium conversion of CO₂ can be shifted further towards CO. For the experiment performed, the product from one set of reaction channels was cooled to ~8°C and the water collected. These gases were then reheated to the original reaction temperature and sent into a second set of reaction channels. To minimize heat requirements, a recuperative heat exchanger was used for both sets of reactions. The results of this approach

¹ Contact Time = Empty Reactor Volume/Reactant Flow at Standard Temperature & Pressure

as compared to predictions are shown in Figure 7. The figure shows an increase of approximately 15% in overall conversion by removing the water and reprocessing the reactor products. Furthermore, the conversion obtained is very similar to that predicted by thermodynamic equilibrium.

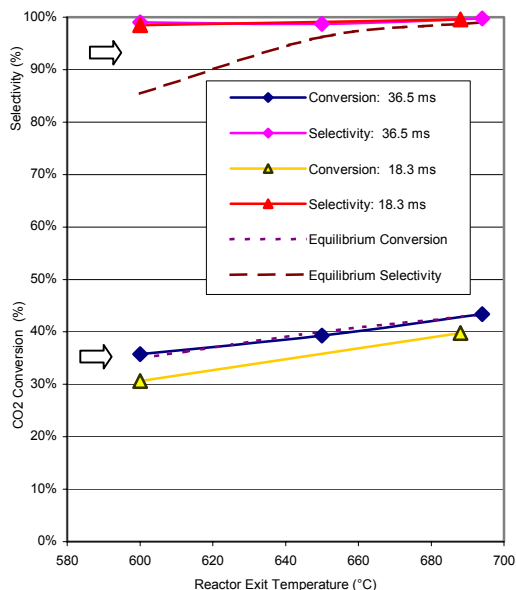


Figure 6. RWGS reaction CO₂ conversion and CO selectivity at H₂/CO₂ ratio= 1 and contact times of 18.3 ms and 36.5 ms.

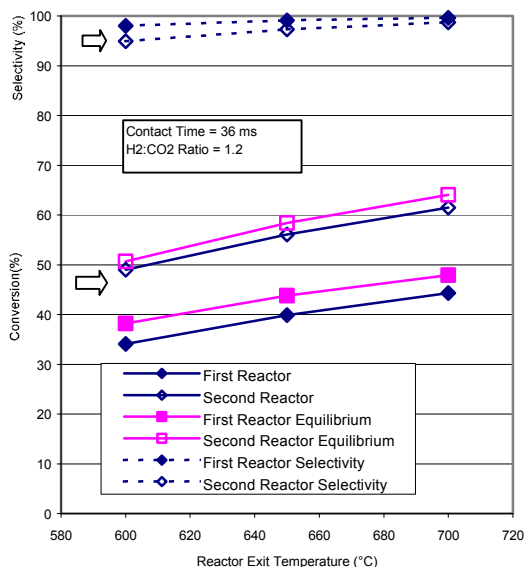


Figure 7. Conversion and selectivity for two RWGS reactors in series removing the water between to increase conversion. Both reactors are at the same temperature. Experimental results are compared to thermodynamic equilibrium.

Sabatier Reaction System Design

The SR reactor was designed to be one-eighth scale for a robotic sample return mission to Mars. The overall dimensions of this one-eighth-scale reactor are 11 x 2.3 x 3.7 cm. A drawing of the reactor is shown in Figure 8. Because the SR is exothermic and strongly limited by equilibrium, the key to high conversions is to provide a means of cooling the reactor over the course of the reaction to maintain its temperature near isothermal. To do this, seven reaction microchannels each were used, interleaved with eight cooling microchannels. To initially heat the reactor, electric rod heaters were placed on either end of the reactor. Once the reaction was initiated, these rod heaters could be turned off as the exothermic reaction maintains the reactor temperature. To control the temperature, coolant flow and temperature is adjusted. Similar to the RWGS reactor, before entering the microchannels, the feed gases passed through a recuperative heat exchanger. The recuperative heat exchanger heats the feed streams with the product streams.

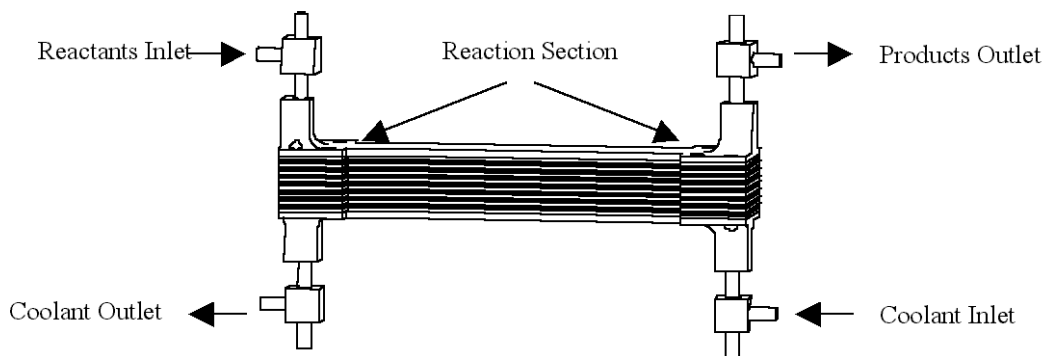


Figure 8. Drawing of the one-eighth-scale Sabatier reactor.

The SR reactor was evaluated over a range of temperatures and contact times at a stoichiometric H₂ to CO₂ ratio of 4. The experiment was run near atmospheric pressure with a pressure range from 115 to 150 kPa, which is approximately the baseline condition for reactor operation on Mars. Due to the exothermicity of this reaction, in some cases, it was difficult to maintain the reactor isothermal. In general, the first axial temperature was 20 to 30°C higher than the subsequent temperatures down the length of the reactor. The experimental results are shown in Figure 9. For comparison, the isothermal equilibrium case and the adiabatic equilibrium case are also plotted. At a contact time of ~ 400 ms, the CO conversion is within experimental error of the equilibrium conversion of 84.9%. As expected, the conversion decreases at lower contact times. To achieve the methane production for 1/8th scale of the sample return mission with this reactor, a contact time of approximately 100 ms is required. This would result in slightly more than 70% conversion in the reactor.

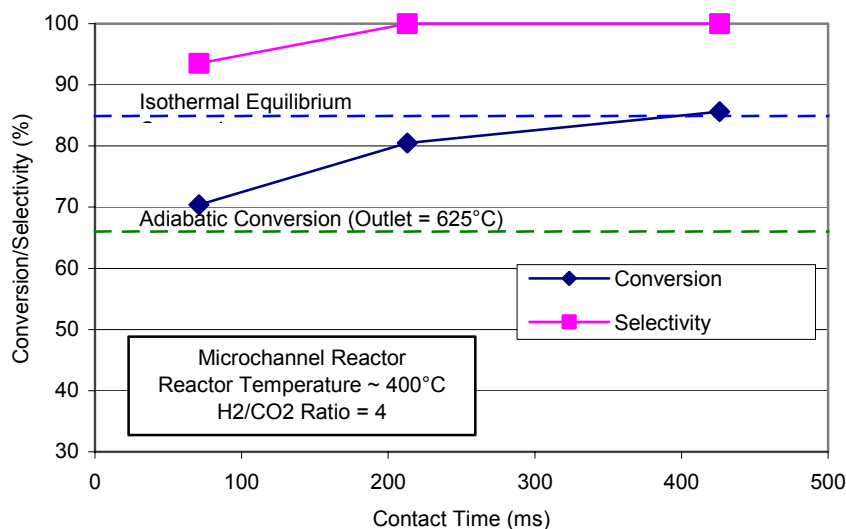


Figure 9. Conversion and selectivity of the SR as compared to thermodynamic calculations.

Separation and Purification Subsystem

Phase Separator - Water Recovery

For purification and separation of the effluent of the RWGS and SR reactors, PNNL is creating a family of MicroCATS technologies that relies on capillary and surface-energy forces. Reduced size and weight are obvious advantages for space exploration, but the small dimensions and high surface area-to-volume ratio in these devices implies that the role of gravity diminishes in favor of capillary, surface, and hydrodynamic forces. This enables chemical processing in low-gravity environments. Furthermore, by controlling the wettability and porosity of the device components, the location of fluids can be controlled, promoting not only the segregation of the process fluids, but also control over film thickness that limits the rate of mass transfer and ease of recovery from process upsets. This technology has been applied to phase separation of liquid from gas, partial condensation, and gas absorption. In each of these devices, liquid channels are created through the use of wettable, porous structures that serve as wicks and/or pore throats (see Figure 10). In all of these devices, gas is allowed to flow adjacent to the liquid in either an open channel or a channel filled with a capture structure. The capture structure is a high void volume porous surface that induces the movement of liquid in the gas channel to the wick or pore throat, an important element for phase separation or condensation. A heat-exchange channel may be placed as needed adjacent to the gas channel (Figure 10) and/or adjacent to the liquid channel. Although development work has been performed for phase separation, partial condensation, and gas absorption, only phase separation and partial condensation will be discussed here.

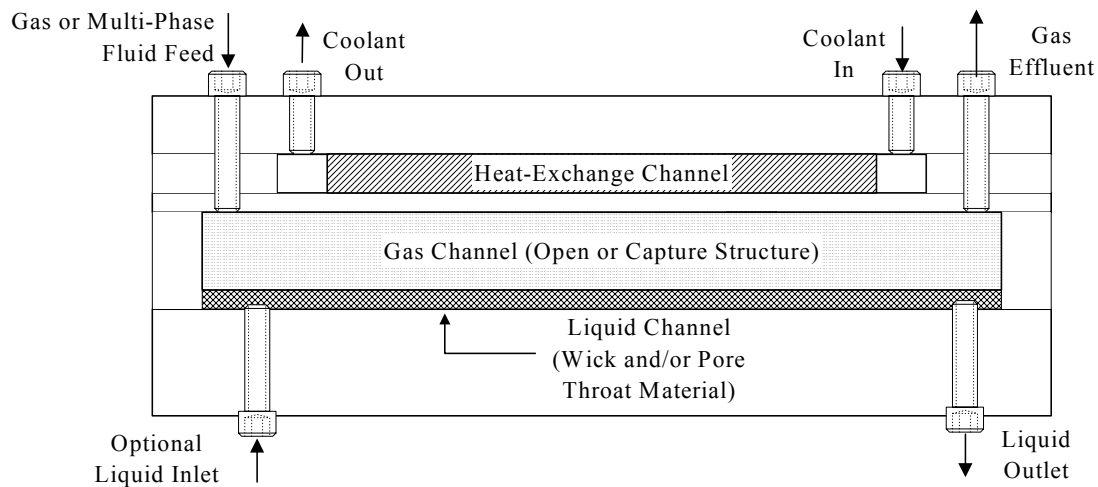


Figure 10. Wicking single microchannel separator shown in co-current flow.

For the NASA ISPP process, water generated in the RWGS and SR reactors needs to be collected for subsequent electrolysis. Since water is readily condensed, the reactor effluent stream is likely to be two phases. Proof-of-concept experiments to separate gas phase from liquid phase were completed using a device similar to that shown in Figure 10 and a two-phase stream consisting of liquid water mixed with air. The mixture was fed to the phase separator through the gas/multi-phase fluid inlet. An acrylic sheet bounded the open gas channel (7.3 cm x 1.4 cm x 0.27 cm) on the upper face, and no heat-exchange channel was present. The liquid channel (8 cm x 2 cm x 0.036 cm) was composed of a pore throat made of sintered stainless steel overlying a stainless steel screen. Phase separation performance was evaluated by collecting water from the gas and liquid-effluent streams and applying a mass balance.

Experiments were conducted by varying the gas and liquid flowrates of the feed stream as well as the pressure difference held across the pore throat. The permeability of the pore throat, which is given by Darcy's law, as well as the hydrodynamics of the system limit the throughput of the device. As can be seen in Figure 11, 100% of the liquid is recovered at high gas-to-liquid Reynolds number ratios. These results suggest complete separation when the liquid flowrate is sufficiently low for a given gas flowrate. Complete separation at higher relative liquid flowrates is also possible, just as long as the liquid occupies only the edges of the gas channel, as occurs in the case of annular flow. The transition from complete to partial separation was correlated with the transition from annular to slug flow, as confirmed by visual observation and similarities to the flow transition maps created by Jayawardena et al. (1997). Figure 11 also illustrates that liquid recovery varies in accordance with Darcy's law. The greater the pressure differences across the pore throat, the greater the liquid throughput at the incipient liquid breakthrough into the gas exit. Gas breakthrough into the liquid outlet occurred only when liquid breakthrough into the gas outlet occurred. Breakthrough was typically observed below the measured bubble-point pressure of the pore throat, most likely due to large pressure fluctuations caused by the two-phase flow in the gas channel.

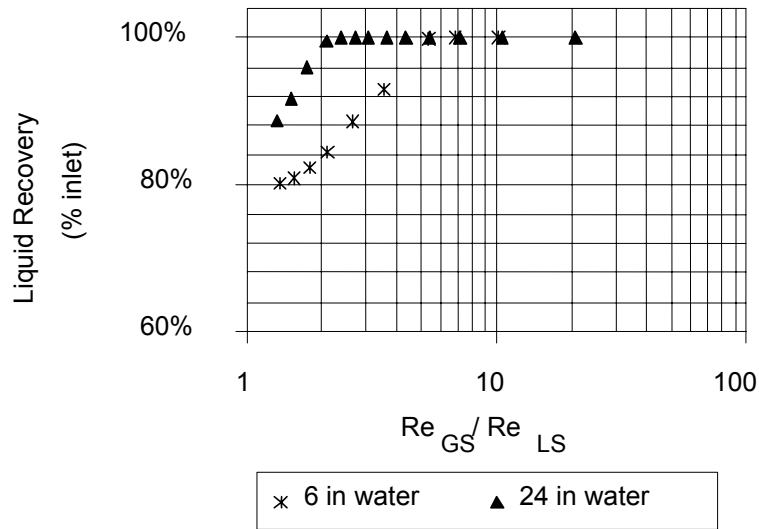


Figure 11. Percent of feed liquid recovered from the liquid outlet for water as a function of gas-to-liquid Reynolds number ratio (Re_{GS}/Re_{LS}) for varying pressure differences across the pore throat.

In cases where the stream consists of both condensable and non-condensable gases, the phase separator (Figure 10) can be modified for partial condensation by placing a heat-exchange channel on the gas side. Proof-of-concept experiments were performed using the configuration shown in Figure 10. Since the required liquid throughput was lower, a wick replaced the pore throat in the bulk of the liquid channel, while a smaller 2-cm x 2-cm pore throat was located at the liquid exit to prevent gas intrusion. To enhance heat transfer, as well as movement of the condensed liquid to the wick, metal screen capture structures were placed in the gas channel. In this way, the device functions as a combined water condenser and phase separator. During complete phase separation, heat fluxes up to $55,000 \text{ W/m}^2$ were obtained, with an overall heat-transfer coefficient of $200\text{-}1000 \text{ W/m}^2\text{-K}$. Gas residence times were 10-60 milliseconds, and the heat-exchanger effectiveness ranged from 87 to 99.6%. The effluent gas was reduced in water content to the saturation point corresponding to the reduced exit temperature.

Summary and Conclusions

Using microchemical and thermal systems is an approach to minimizing the weight and volume of an ISPP system. By taking advantage of short thermal and molecular diffusion distances, reduced thermal mass, and capillary effects, the sub-systems studied can be smaller and more efficient. The single-channel adsorption studies indicate that the multi-cell CO_2 thermochemical compressor that is being fabricated will meet the required throughput of CO_2 of an eighth-scale system with a compression ratio of 10. Through a second similar system in series, the required compression ratio may also be met. The RWGS and SR have been successfully demonstrated in a microchannel reaction device. Because of the improved heat transfer, close to isothermal conditions are possible, allowing near-equilibrium reaction conversions with small reactors. The use of wicking devices in vapor/liquid separators has resulted in 100% liquid recoveries at gas-to-liquid ratios down to ~ 2 . Similarly, high efficiencies have been obtained when this device is configured for partial condensation.

This is just a status report of current progress. Future work will be required for the subsystems described here as well as other required sub-systems. This future work will emphasize scale-up from single channel to full-scale, continued improvements of thermal efficiency, and the fabrication of a breadboarded system.

Acknowledgments

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