Rotary Drum Separator and Pump for the Sabatier Carbon Dioxide Reduction System

Abstract

A trade study conducted in 2001 selected a rotary disk separator as the best candidate to meet the requirements for an International Space Station (ISS) Carbon Dioxide Reduction Assembly (CRA). The selected technology must provide micro-gravity gas/liquid separation and pump the liquid from 10 psia at the gas/liquid interface to 18 psia at the wastewater bus storage tank. The rotary disk concept, which has pedigree in other systems currently being built for installation on the ISS, failed to achieve the required pumping head within the allotted power. The separator discussed in this paper is a new design that was tested to determine compliance with performance requirements in the CRA. The drum separator and pump (DSP) design is similar to the Oxygen Generator Assembly (OGA) Rotary Separator Accumulator (RSA) in that it has a rotating assembly inside a stationary housing driven by a integral internal motor. The innovation of the DSP is the drum shaped rotating assembly that acts as the accumulator and also pumps the liquid at much less power than its predecessors. In the CRA application, the separator will rotate at slow speed while accumulating water. Once full, the separator will increase speed to generate sufficient head to pump the water to the wastewater bus. A proof-of-concept (POC) separator has been designed, fabricated and tested to assess the separation efficiency and pumping head of the design. This proof-of-concept item was flown aboard the KC135 to evaluate the effectiveness of the separator in a microgravity environment. This separator design has exceeded all of the performance requirements. The next step in the separator development is to integrate it into the Sabatier Carbon Dioxide Reduction System. This will be done with the Sabatier Engineering Development Unit at the Johnson Space Center.

Introduction

Phase separation in micro-gravity has always been considered among the NASA community as an area of inherent risk that requires adequate component development. The Sabatier CO2 Reduction Assembly (CRA) is a component of an Air Revitalization System that recovers valuable water from what would otherwise be waste gases, namely metabolic carbon dioxide and the electrolytic bi-product hydrogen. In addition to separating the waste gas from the product water, the phase separator component must also deliver the water to a bus that is maintained at higher pressure than the CRA.

The NASA Johnson Space Center (JSC), the NASA Marshall Space Flight Center (MSFC) and Hamilton Sundstrand Space Systems International (HSSSI) have been jointly developing the Sabatier CRA to meet a Technology Readiness Level of 6 (prototype tested in a relevant environment). One of the higher priority risk mitigation tasks is the development of a phase separator that meets all of the performance requirements imposed by system operating modes.

Requirements

The Sabatier Carbon Dioxide Reduction Assembly takes in the hydrogen by-product from electrolytic oxygen generation and metabolic carbon dioxide that is concentrated by a molecular sieve bed and reacts them to form methane and water. The reactor products are cooled in a heat exchanger where the water product condensed to liquid. The liquid water and methane gas are then separated in a rotary phase separator, with the water being delivered to the water bus and the methane released out the vacuum vent duct. Figure 1 shows a simplified schematic of the Sabatier CRA.

Simplified Sabatier Carbon Dioxide Reduction Schematic

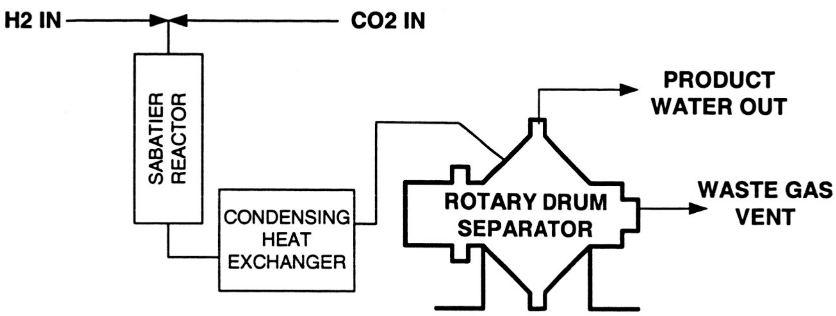

Figure 1 – The Rotary Drum Separator / Pump provides product water to the water bus and liquid free gases to the waste vent.

The Sabatier CRA operates at below ambient pressure at all times for safety reasons. This condition minimizes leakage of flammable gases into the rack environment. The wastewater tank, which is the recipient of the CRA product water, is a bellows type tank whose pressure varies depending on the amount of water in the tank. The main design driver for the phase separator is the ability to efficiently pump the product water from the 10 psia gas liquid interface pressure to the maximum of 17.7 psia in the waste water accumulator tank. There is some additional pressure drop between the systems due to valves. The total pressure rise used as the design requirement for this device is 12 psid.

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Since the objective of the CRA is to recover as much water as possible, it is undesirable to lose water in the form of steam out the methane vent. The design goal, therefore, is to limit the fluid temperature rise in the separator to no more than 5 degrees F. The device must also perform efficiently as a separator. Previous pitot type separator designs were inadequate in the absolute separation capability. Typically the backpressure on the device had to be adjusted to achieve complete separation of one stream at the expense of the other. The rotary drum separator has proven to achieve better separation than a pitot. The system requirements imposed on the device are <0.5% by volume gas inclusion in the product water and <0.5 cc/event or 0.5 cc/hr water carryover in the gas.

The acoustic profile of the separator is very important as many rotating devices currently installed on ISS exceed the required 40 dB specification curve. The phase separator requirement is NC40 minus 3 dB for steady state, 72 DBA intermittent for less than 15 minutes per day.

Other design requirements are derived to meet the current control scheme. It is desired to collect water for at least 15 minutes before pumping the water to the waste tank. This leads to an accumulation volume requirement of three cubic inches. The condensing heat exchanger is immediately upstream of the separator. When the CRA is in Standby mode, water vapor could continue to collect in the heat exchanger tube and the flow all at once to the separator once Process mode is selected. The separator therefore has a requirement to accept a slug of 0.7 cubic inches without violating the separation requirement.

A summary of the Rotary Drum Separator and Pump design requirements are listed in Table 1.

Table 1 Phase Separator Design Requirements

Category	Requirement
Water Carryover	Less than 0.5 cc/event or 0.5 cc/hr
Gas Inclusion	<0.5% by volume (@ Steady State, excludes initial dry start)
Water Storage Capacity	>3 cubic inches, measurable by DP
Slug Capacity	0.7 cubic inches (1/4 volume of 8' of 0.25" OD plumbing)
Pressure Rise, inlet to water outlet	>12.0 psid
Pressure Drop, inlet to gas outlet	< TBD psid
Life	>10 years, >40,000 ON/OFF cycles
Dry Operation	Capable of 10 dry starts which include 8 minutes of dry operation each
Particle Tolerance	200 micron
Noise	NC40 minus 3 dB for steady state, 72 dBA intermittent (<15 minutes per day)
Start-up Speed	Between 1 and 5 seconds
Gas Temperature Rise	Less than 5 F at minimum steady flow
Water Temperature Rise	Less than TBD F at minimum steady flow
External Seals	Double
Freezing Tolerance	No performance degradation after repeated freeze/thaws
Explosion Pressure Tolerance	786 psia with no degradation (assumes 15.2 psia initiation pressure)
Vibration Emissions	The CRA ORU must meet the vibration emission requirements

The phase separator, pictured below in Figure 2, is the result of the design effort to meet the above listed requirements.

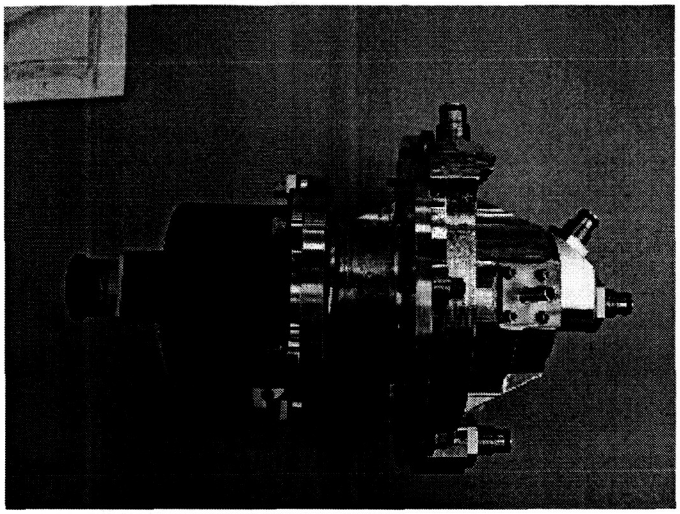

Figure 2 – The Sabatier Phase Separator developed as part of the Sabatier risk mitigation activities for Advanced Life Support.

Separator Design

The separator design was based on the rotary disk technology that was originally developed for the Mostly Liquid Separator (MLS), which incorporates a number of disks that rotate within a stationary housing. The MLS design is converse to the pitot type separator in which the pitot is stationary inside a rotating bowl. The Rotary Drum Separator and Pump diverges again in that the disks are now replaced with a drum that provides the accumulator volume. In the center, a larger diameter pumping section is fabricated integrally into the drum. The drum is mounted on a shaft that is supported by hydrodynamic bearings. An integral motor outboard of one of the bearings allows leak free operation at sub-ambient pressure. The hollow shaft forms the gas outlet tube with its outlet located at the opposite end from the motor. The housing consists of two stainless steel sections that hold the bearings, provide passageways for fluid circulation and enclose the drums. The water outlet port is tangential to the housing outer diameter and as such collects the water at maximum velocity head. There is also a port normal to the disk rotation that serves as a static pressure port. The internal volume of the separator will hold approximately 170 cc of water when full with a working volume of 70 cc.

The separator will operate on a two-speed schedule. At low speed, about 1000 rpm, the separator will create enough of an artificial gravity field to effectively separate the gas and liquid phases. The gas port is always open when the Sabatier is in process mode generating water; therefore the vent gases flow through the separator with very little pressure drop. Pressure taps at the gas outlet and drum outer diameter allow monitoring of the liquid level in the separator via differential pressure. The pressure vs. volume has been calibrated in both 1-g and 0-g environments. Once the liquid level of the separator reaches the high end of the operating range, the controller will increase the speed of the separator to about 2400 rpm. At this speed, the pressure generated by the centrifugal and velocity forces of the liquid in the paddle section of the drum is sufficient to overcome the system backpressure and the liquid empties from the separator. The high speed condition is maintained for a sufficient length of time that the liquid level drops to the low end of the operating range.

Phase Separator Performance

The Sabatier development phase separator was tested under various conditions of flow, pressure and attitude in order to assess the performance against the previously stated requirements. Table 2 lists the performance achieved with the phase separator against each of the requirements.

Table 2 – Phase Separator Performance

Category	Requirement	Performance
Water Carryover	Less than 0.5 cc/event or 0.5 cc/hr	No carryover except during slug flow (see below). Maximum water carryover during slug flow is 0.2 cc/event.
Gas Inclusion	<0.5% by volume (@ Steady State, excludes initial dry start)	1 cc gas/180 cc liquid
Water Storage Capacity	>3 cubic inches, measurable by differential pressure	Actual usable volume is 4.27 cubic inches (70 cc) minimum
Slug Capacity	0.7 cubic inches (1/4 volume of 8' of 0.25" OD plumbing)	0.7 in3 (11 cc) slug results in 0.2 cc carryover/event
Pressure Rise, inlet to water outlet	>12.0 psid	20 psid achieved at 2400 rpm
Pressure Drop, inlet to gas outlet	< TBD psid	0.1 psid at maximum gas flow of 9 std l/min
Life	>10 years, >40,000 ON/OFF cycles	Not yet tested.
Dry Operation	Capable of 10 dry starts which include 8 minutes of dry operation each	Not yet tested.
Particle Tolerance	200 micron	Not yet tested.
Noise	NC40 minus 3 dB for steady state, 72 dBA intermittent (<15 minutes per day)	Not yet tested.
Start-up Speed	Between 1 and 5 seconds	Not tested in this configuration, will depend on motor controller design
Gas Temperature Rise	Less than 5 F at minimum steady flow	4F at 2.7 std l/min
Water Temperature Rise	Less than TBD F at minimum steady flow	6F during water pump out.
External Seals	Double	Development Separator includes double seals at all interfaces
Freezing Tolerance	No performance degradation after repeated freeze/thaws	Not yet tested.
Explosion Pressure Tolerance	786 psia with no degradation (assumes 15.2 psia initiation pressure)	Stainless steel housing analytically assessed to withstand 300 psi pressure rise
Vibration Emissions	The CRA ORU must meet the vibration emission requirements	Not yet tested.

One of the goals of the rotary drum pump/separator design was to minimize the power required for pumping. Previous versions of the separator used as much as 160 Watts to achieve 18 psi of pumping head. After the pressure requirement was lowered to 12 psid, the power consumed was still over 120 Watts. The new drum design has achieved pumping pressure of 15 psid using only 80 Watts.

Figure 3 is a plot of the separator pressure and power consumption during a period of several hours. The steady flow rate of water and gas to the separator slowly filled the drum. Once full, the test operator would increase the separator speed to empty the drum.

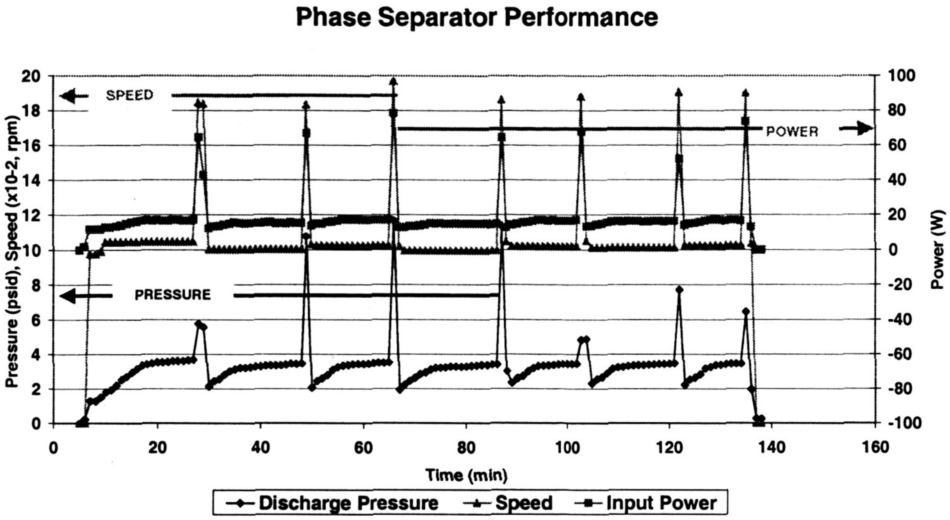

Figure 3 – The phase separator achieves the required pumping pressure while maintaining a low steady state power consumption.

Gas carryover was measured by plumbing the discharge flow under an inverted burette. The amount of gas collected was 1 cm3 when a total of 180 cm3 of water product was pumped out of the separator.

Water carryover was measured by passing the product gas through a trap. No water carryover was detected during steady state operation. This was observed under test operating conditions of 10 ml/minute water mixed with 2.7 std liter/minute gas at the separator inlet. This test was performed in three orientations: motor-separator horizontal, motor at top, motor at bottom.

The gas side pressure drop was measured to be 0.8 inches water column at the maximum vent gas flow of 2.7 std liter/minute. At 9 std l/min, which would be the maximum gas flow under system failure conditions, the pressure drop is 2.6 inches water column.

The phase separator passes the slug challenge of 11 cc liquid with gas flow rates of up to 9 slpm. The amount of liquid carryover observed during this test was 0.2 cm3.

The stainless steel housing was designed to minimize the weight of the component. The stress analysis indicates that the maximum pressure capability of this development separator is 300 psi. The flight design will have to be modified to increase the proof pressure capability to 786 psi while minimizing weight.

Microgravity Testing Aboard the KC135

Microgravity phase separation is considered by NASA to be an area of risk in the development of the Sabatier Carbon Dioxide Reduction Assembly. MSFC and HSSSI coordinated a microgravity test of the proof-of-concept (POC) phase separator aboard the KC135. The following were the test objectives for the flight.

1. Steady state operation
2. Derive volume vs. pressure data in reduced gravity
3. Slug flow capability
4. Examine reduced gravity pump out for entrained gas bubbles
5. Start - Stop operation in reduced gravity
6. Increase customer confidence in the separator design

The Sabatier POC separator was flown for 4 days on NASA KC-135. All the test objectives listed above were met as the phase separator performed as expected under all test conditions. There was no liquid water observed in the gas outlet during normal operation. The liquid water pumped out proved to be free of entrained gas.

Figure 4 shows the authors attending to data collection during one of the zero-g dives of the KC135 flight. Pressure data collected during the zero-g segments was used to generate a correlation for liquid level. The separator motor was stopped and restarted during zero-g to determine if liquid would migrate to the gas outlet. There was no evidence of liquid carryover during any of these tests.

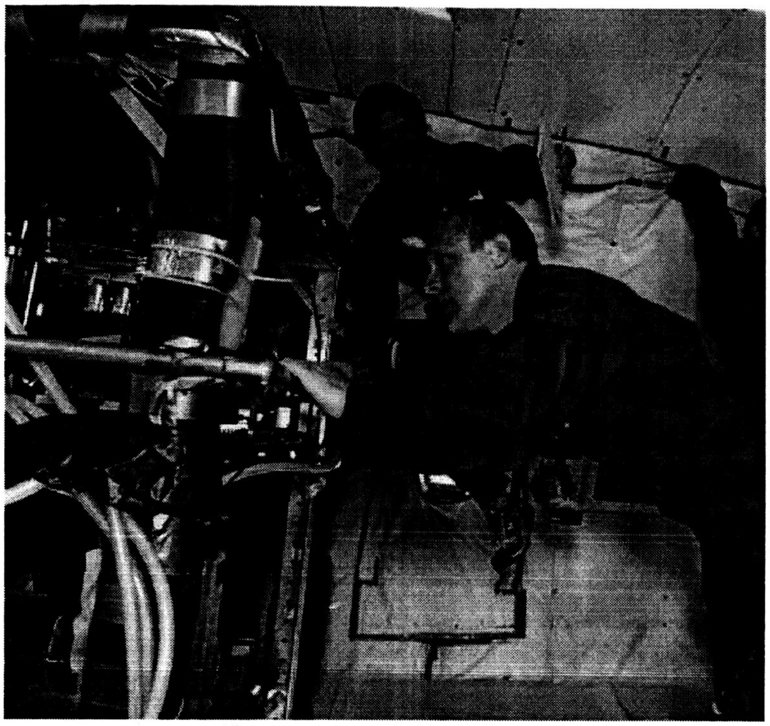

Figure 4 – The phase separator achieved all of its performance goals during weightless testing aboard the KC135.

Figure 5 below shows the correlation between the pressures developed at various liquid levels in the separator under 1-G and 0-G conditions. Either operating environment is conducive to correlating pressure to liquid volume and therefore, pressure measurement is a viable strategy for system control.

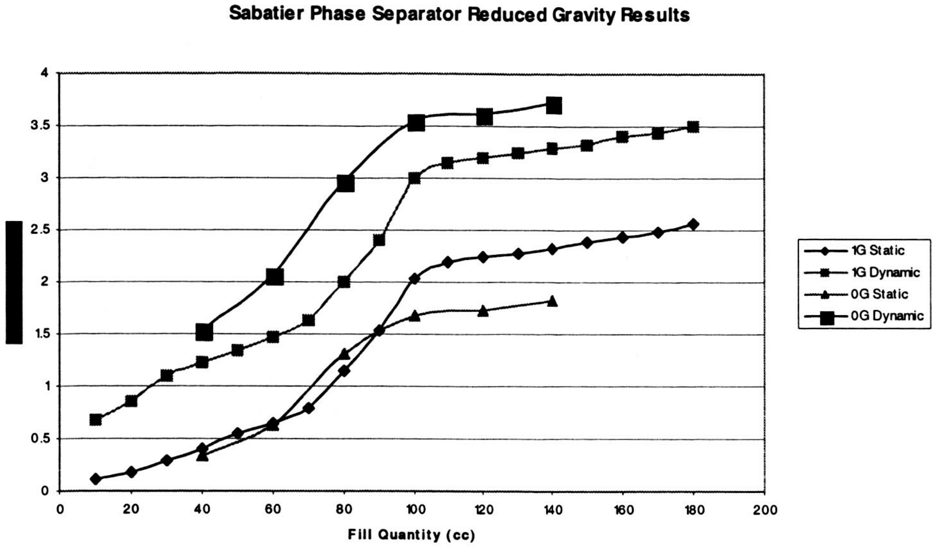

Figure 5 – Pressure measurement is a viable strategy for determining liquid level in either 1-g or 0-g.

Conclusion

The Sabatier CO2 Reduction Assembly (CRA) presents a unique set of operating requirements for a phase separation that were not achievable with any of the existing rotary or passive phase separator designs. A development program funded by the NASA Johnson Space Center and managed by Hamilton Sundstrand Space systems International resulted in the development of a new phase separator design with unique low flow, high pressure pumping capability. This separator has met the challenge of developing 20 psid of pumping head using under 100 Watts input power. The phase separator development program has mitigated the risks inherent in micro-gravity phase separation. This has been but one task in the Sabatier risk mitigation and technology development plan intended to raise the Technology Readiness Level of the CRA to Level 6 (Prototype demonstration in a relevant environment).

Acknowledgement

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For more information on Sabatier Carbon Dioxide Reduction Assembly system requirements, see Murdoch, et. al. (1). For more information on other HSSSI microgravity phase separation devices, see Samplatsky, et. al. (2).

References:

1) Murdoch, K., Smith, F., Perry, J., Green, S., "Assessment of Technology Readiness Level of a Carbon Dioxide Reduction Assembly (CRA) for use on International Space Station," 2004-01-2446, International Conference on Environmental Systems, 2004.

2) Samplatsky, D., Dean, W., "Development of a Rotary Separator Accumulator for Use on the International Space Station," 2002-01-2360, International Conference on Environmental Systems, 2002.