Pressure Controlled Heat Pipes

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In a Variable Conductance Heat Pipe (VCHP), a Non-Condensable Gas (NCG) is added to the heat pipe to allow the conductance to vary. A Pressure Controlled Heat Pipe (PCHP) is a VCHP variant, where the heat pipe operation is controlled by varying either the gas quantity or the volume of the gas reservoir. This paper will discuss two applications for PCHPs: 1. Precise Temperature Control, and (2) Switching thermal power between multiple sinks. A prototype aluminum/ammonia PCHP was built and tested to demonstrate the capability of controlling the evaporator section of an aluminum/ammonia pressure controlled heat pipe to milli-Kelvin levels over an extended period of time. The external (simulated radiator or heat sink) temperature was varied and the heat input into the evaporator section was varied during those tests. Temperature set point changes were also demonstrated. PCHPs can also be used to switch power between multiple high temperature reactors. In a second program, a heat pipe solar receiver was designed to accept, isothermalize and transfer the solar thermal energy to reactors for oxygen production from lunar regolith. The receiver has two PCHPs and two CCHPs to supply heat to two reactors. During operation, one reactor is producing hydrogen at low solar power, while the other reactor is warming up a fresh batch of regolith. The PCHPs switch power between the two reactors as required.

I. Introduction

The only fluid in a conventional, Constant Conductance Heat Pipe (CCHP) is the working fluid. There are a number of useful heat pipe variations when a Non-Condensable Gas is added, for example in Variable Conductance Heat Pipes , Gas-Loaded Heat Pipes, and Pressure Controlled Heat Pipes.

A. Pressure Controlled Heat Pipes

A Pressure Controlled Heat Pipe (PCHP) is essentially an actively controlled VCHP. The operating principles are similar. The vapor/non-condensable gas (NCG) interface position in the condenser moves to vary the conductance of the heat pipe. When the heat load increases or the radiator sink temperature increases, the temperature (and pressure) of the heat pipe also increases. In a VCHP, the increase in vapor pressure forces more of the non-condensable gas into the reservoir, which moves the vapor/non-condensable gas interface further into the condenser. In a PCHP, the control system senses this increase (or decrease) in pressure and/or temperature and actively changes either the gas charge in the reservoir or the volume of the reservoir to maintain the operating temperature precisely at the set point.

There are two ways to achieve precise temperature control using a pressure controlled heat pipe (PCHP). One is to modulate the amount of NCG in the reservoir; and, the other is to modulate the volume of the reservoir. The modulation of the amount of NCG in the reservoir is the conventional means of making a terrestrial based PCHP. In these applications, primarily high-temperature precision-calibration systems, the NCG is added to or removed from the reservoir by means of a high pressure gas cylinder and a vacuum pump.

The challenge for adapting this type of control system for use in space is to miniaturize the NCG supply tank and vacuum pump. More likely, a space-based system would incorporate a small compressor and a small reservoir. The reservoir would be high pressure biased so that when NCG must be added to the PCHP, a simple solenoid valve

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would be activated and NCG would flow back into the PCHP. If NCG needs to be removed, the compressor would cycle on and pump NCG from the PCHP to the small reservoir. A sketch of the concept is shown below in Figure 1.

Modulation of the reservoir volume is the other method of controlling the PCHP. In this concept, the NCG reservoir includes a bellows structure. A linear actuator is used to drive the position of the reservoir, thus modulating the volume of the reservoir. This concept is relatively simple and requires only one active device. The challenge for this concept is to design and build a bellows type reservoir (mass and volume optimized), that can be varied with minimal power usage and with fine enough resolution to achieve milli-Kelvin control. A sketch of the concept is shown below in Figure 2. The bellows system was selected for the PCHPs, since it is simpler to implement for spacecraft applications.

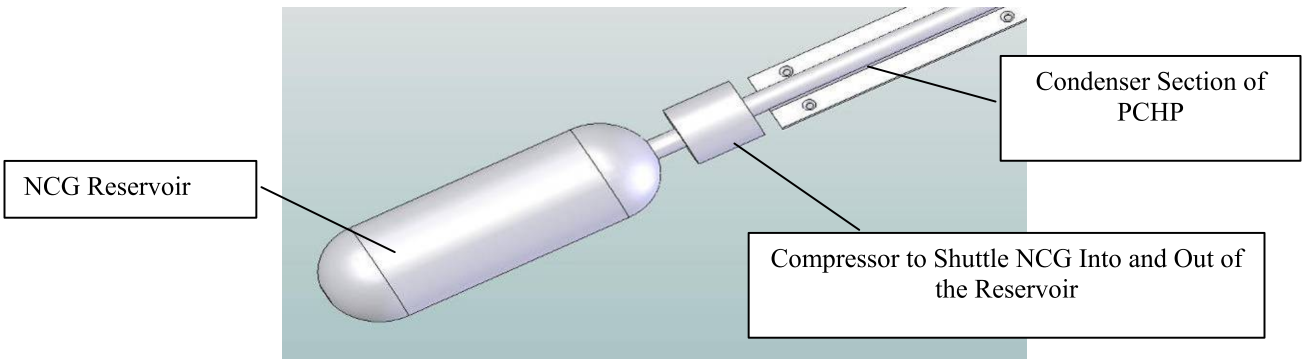


Figure 1. NCG Gas Modulated PCHP.

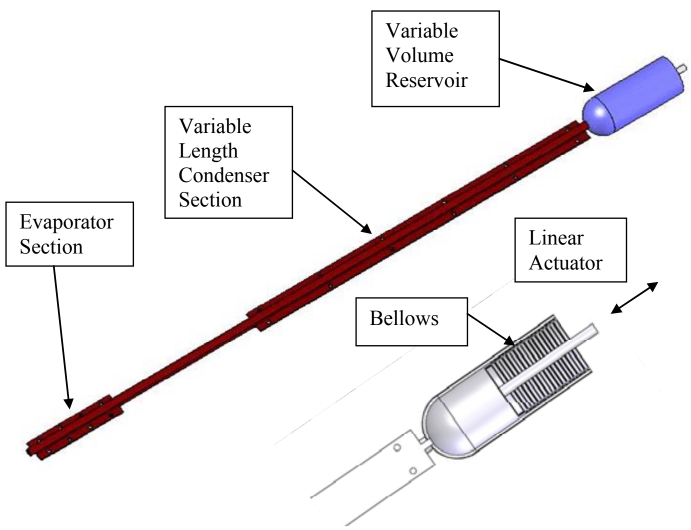


Figure 2. Volume Modulated PCHP.

II. PCHPs for Precise Temperature Control

Regardless of the method used, it is the variable reservoir volume or variable NCG charge that allows the PCHP to define a set point (over a wider temperature range), and to control temperature very precisely about that set point. In contrast, even with an unusually large reservoir, conventional VCHPs in a thermal network have a fixed set point, and are not capable of precision temperature control to the milli-Kelvin level. The differences between the PCHP and VCHP for precise temperature control are highlighted in Table 1.

Pressure Controlled Heat Pipes have three major advantages over conventional CCHP, VCHP, and Loop Heat Pipe (LHP) solutions and those utilizing cold biasing and trim heaters:

- Precise temperature set point control to the milli-Kelvin level without power-wasting trim heaters and without a massive reservoir.

- Nearly instantaneous reaction to changes in the environmental conditions (low thermal mass lag).
- Ability to adjust the set point in-situ. Thermal analysis and ground testing can differ by as much as ± 10K from the results in space. The PCHP compensates for these discrepancies in real time after the satellite has been placed in orbit.

Table 1: VCHP versus PCHP Comparison for Precise Temperature Control.

Parameter	**VCHP**	**PCHP**
Variable Conductance	Yes	Yes
NCG Reservoir	Yes	Yes
Reservoir Volume	Fixed	Variable
NCG Charge	Fixed	Variable
Temperature Control	+/- 1.0 K	+/- 0.005 K
Set Point Control	None	Yes

The control scheme for the PCHP for precise temperature control is shown schematically in Figure 3. The PCHP is an enhancement to a conventional Variable Conductance Heat Pipe (VCHP) that adds the ability to actively control the reservoir volume, and subsequently the thermal resistance of the heat pipe condenser. With a suitable feedback control system, the PCHP can achieve milli-Kelvin temperature control of evaporator temperature while compensating for changes in sink temperature or input power without the need for the large VCHP reservoir.

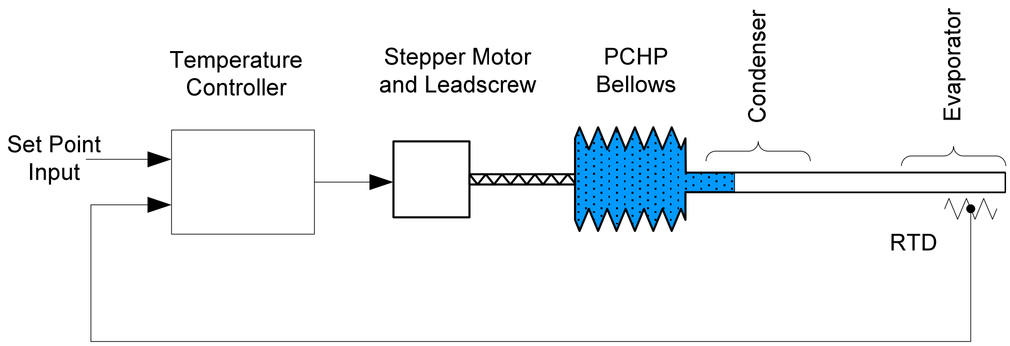


Figure 3. Schematic of Pressure Controlled Heat Pipe Showing Feedback Control of Reservoir Volume and Condenser Thermal Resistance.

B. PCHP Design for Precise Temperature Control

The design requirements, shown in Table 2, were selected for a hypothetical but typical spacecraft cooling application in low earth orbit. The design parameters for the PCHP are shown in Table 3.

Table 2: Fundamental PCHP for Temperature Control Design Requirements.

Parameter	Value
Evaporator Temperature Stability	0.001K
Evaporator Input Power	50-150 Watts
Evaporator Temperature	20°C.
Sink Temperature	-40°C to 0°C.
Life	10 years minimum
End Use	Small Satellite on Low-Earth Orbit
Number of Orbits	~58,400
Working Fluid	Ammonia
Evaporator	1.5 in. wide by 6 in. long
Condenser	1.5 in. wide by 12 in. long

One of the flight-weight devices is shown below in Figure 4. It is mounted on a test fixture with electrical heaters at the evaporator and a liquid nitrogen (LN) chill block at the condenser. Heat from the stepper motor is rejected to the condenser through the cooling strap. The bellows is contained in the bellows capsule, which assures alignment and prevents overstressing due to accidental over-travel. The PCHP body is bent so that the completed device can fit in a particular vacuum system at Goddard Space Flight Center (GSFC).

Table 3: Fundamental PCHP for Temperature Control Parameters.

Evaporator Length	6" (150 mm)
Condenser Length	6" (150 mm)
Overall Length	16" (400 mm)
Extrusion diameter	½" (12.5 mm)
Flange Width	1.5" (38 mm)
Working Fluid	Ammonia, 7.4 gm[1]
Stepper Motor	Size 23
Bellows	SS-1000-50-44
Bellows Displacement	8.98 cm^3
Reservoir Average Volume	110 cm^3
Condenser Volume	5.22 cm^3
Reservoir/Condenser Volume Ratio	29:1

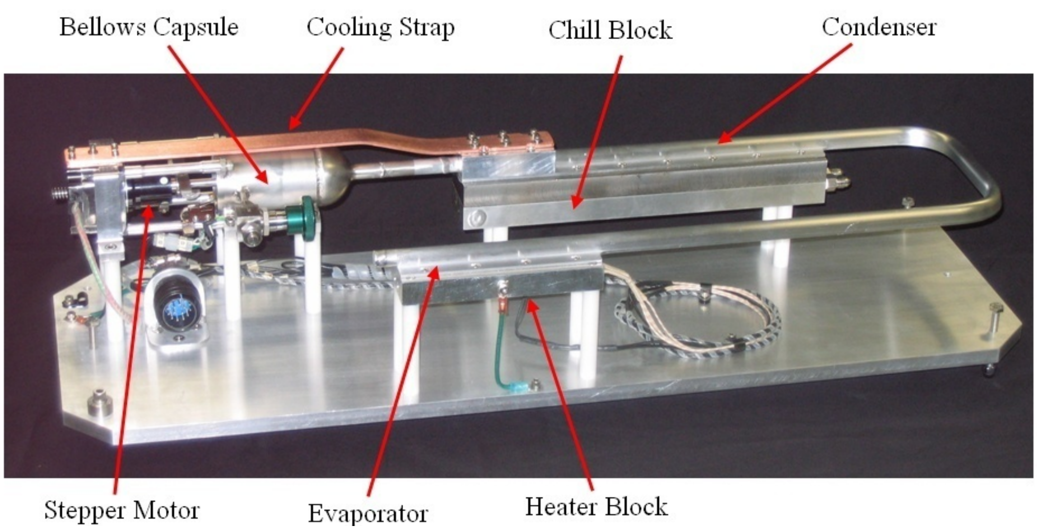


Figure 4: Photograph of PCHP on its Test Fixture.

C. PCHP Qualification Tests

One of the objectives of the program was to demonstrate that the components used can be flight qualified and that they will have a long life in a flight environment. In addition to the thermal control tests, discussed below, the following tests were conducted:

- Proof Pressure Testing.
- Cycle testing candidate bellows assemblies to demonstrate that they can withstand the number of flexures required over a 10 year life.
- Cycle testing the selected stepper and drive to demonstrate operation in vacuum.
- Shock and vibration testing.

Proof Pressure: The maximum operating temperature was 45°C (P_{Sat} = 1.78 MPa). Proof pressure tests were conducted at 61°C, where the saturation pressure is 1.5 times higher (P_{Sat} = 2.68 MPa).
Bellows Fatigue Testing: Tests were conducted to verify that the bellows and other components used to form the variable volume reservoir could withstand the relatively large number of mechanical cycles without experiencing

problems due to fatigue. The bellows testing apparatus is shown in Figure 5. The tests were conducted with a 0.58 MPa pressure in the bellows. Several different bellows were tested. The final bellows tested ran for over 3,300,000 cycles with no sign of failure.

Stepper and Driver Testing: Tests were conducted with the PCHP installed in a thermal vacuum system to demonstrate operation in a relevant environment. A copper strap was installed to cool the motor; see Figure 4. The PCHP operated for over 300 hours in a vacuum environment. The test involved running the motor between two limits ½" apart once every three seconds, for one full cycle every six seconds. The average power dissipated was about 4.8 W. No start-up problems were observed, and the motor remained cool. Note that this power was for an inexpensive stepper device; flight devices will use less power.

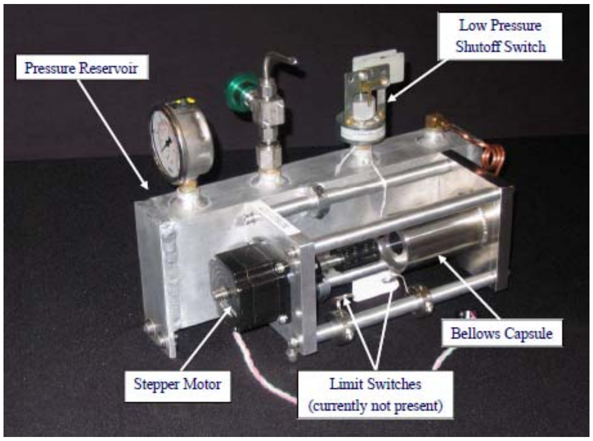


Figure 5. Bellows Testing Apparatus.

Shock and Vibration Testing: For the shock and vibration testing, a survey was conducted of small satellite shock and vibration spectra for the electronics deck or the heat pipe mounting surfaces. That data was combined into a composite or most typical spectrum that was used as the test levels for the PCHP. The data is summarized in Table 4.

Table 4: Random vibration spectrum and shock test levels.

Random Vibration Spectrum	
Frequency (Hz)	g^2/Hz
20	0.026
50	0.16
800	0.16
2000	0.026
grms	15.3
Duration	120 sec/axis

Shock Spectrum	
Frequency (Hz)	Shock Level (G's)
100	50
1000	1000
1500	1000
10000	1000

The vibration test article itself is shown in Figure 6. It consists of the same stepper motor, bellows capsule, mounting feet, and body extrusion. Several changes were made to simplify testing:

- The body extrusion was shortened to allow it to fit within the volume of the available exciter head.
- The test article did not include the limit switches used to detect stepper position.
- The test article included a fill valve which was fastened to the base plate, rather than the pinch and weld planned for a deliverable article.

None of these changes were considered significant to the purpose of the test. The component most in need of qualification was the bellows and stepper drive.

The ammonia working fluid was removed prior to vibration testing and replaced with 10.03 ±1 gm of R134a refrigerant with a 1.09 MPa nitrogen overpressure, that simulated the mass and vapor pressure of ammonia. The stepper motor was ran until the bellows were in their parked position, with the bellows piston hard against the stop. That simulated the launch-ready position.

The PCHP test article was subjected to performance testing before and after vibration. This testing consisted of dryout or maximum power, temperature sensitivity, and bellows deflection measurement. The results of both tests are summarized in Table 5. It shows that there was essentially no change in PCHP performance due to vibration testing. The maximum power was nearly identical and the measured piston displacement was the same. While the temperature change was significantly larger after testing, this was found later to be attributable to changes in the exact position of the gas front due to recharging the fluids, and is not believed to be significant to this test.

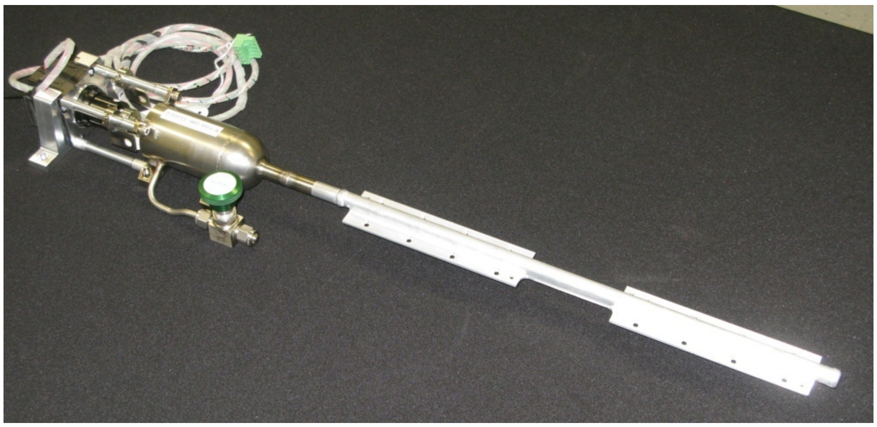


Figure 6: PCHP Vibration Test Article with Full Size Drive and Motor and Reduced-Length Body Extrusion.

Table 5: Summary of Pre-vibration and Post-vibration performance.

Parameter	Pre-Test	Post Test
Maximum Power	387 ± 12 Watts	368 ± 2 Watts
Sensitivity	0.19°C	0.27°C
Bellows Displacement	0.477 in.	0.480 in.

D. PCHP Temperature Control

The test setup is shown in Figure 7. The PCHP was mounted to a rigid aluminum fixture with screws at each corner to precisely adjust the PCHP inclination. The PCHP evaporator and condenser flanges were bolted to rectangular aluminum blocks that supply heat and serve as a heat sink.

- Cartridge heaters are inserted into holes bored in the evaporator block. Power is supplied to the heaters by an external control box which contains a variable transformer and a Watt transducer.
- The condenser block was cooled by flowing cold gaseous nitrogen through holes bored in the block.
- An array of thermocouples were mounted to the top of the heat pipe extrusion to measure evaporator, condenser, and adiabatic temperatures. (3 evaporator, 2 adiabatic, 8 condenser). The thermocouples were made of 26-gage type T thermocouple wire with welded, bare junctions. Additional thermocouples were mounted to the cooling strap and motor, and a 100Ω thin film (Minco S667) 3-wire Resistance Temperature Detector (RTD) was mounted to the top of the PCHP between the first and second evaporator thermocouples.

The PCHP had excellent temperature control during the thermal vacuum tests. Figure 8 compares the open loop and closed-loop response of the PCHP over variations of input power. This PCHP is able to maintain a steady evaporator temperature (measured by the RTD) over input powers ranging from 50 to 125 Watts. In the figures, Open Loop refers to the no control case, or behavior as a passive VCHP, and SP refers to the Set Point Temperature in closed loop mode.

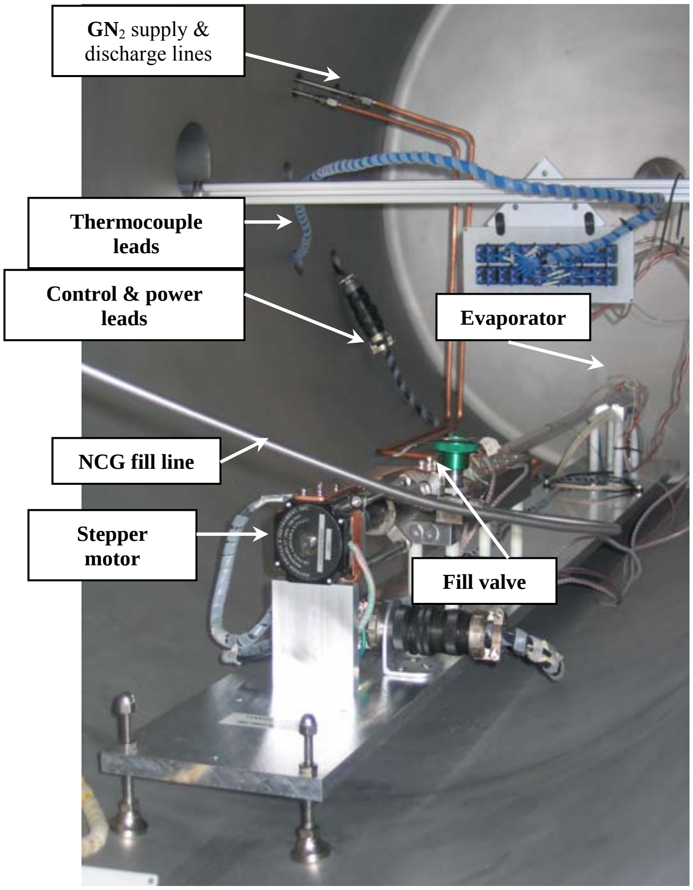


Figure 7: FW-2 PCHP mounted in vacuum chamber and ready for testing.

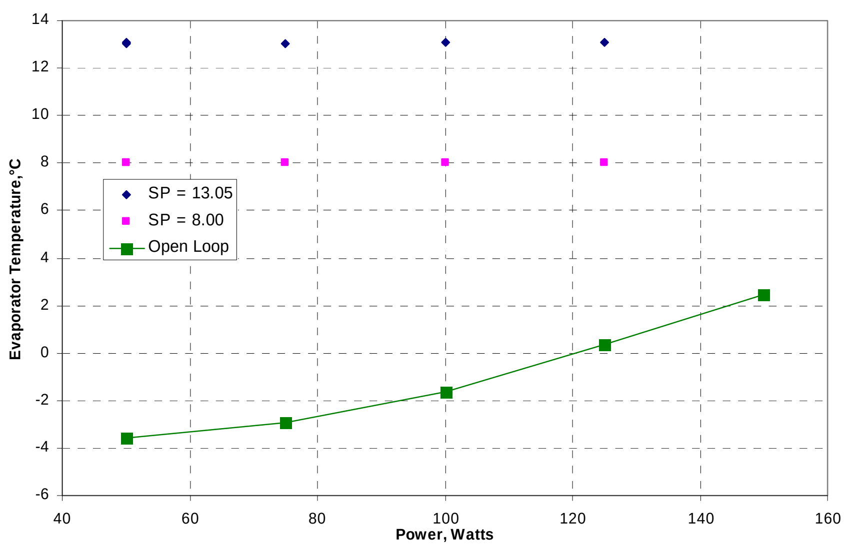


Figure 8: Comparison of Open Loop and Closed Loop Response of the PCHP in vacuum over changes of input power.

III. PCHPs for Power Control at High Temperatures

A second application for PCHPs is their ability to switch power between different reactors at high temperatures for In-Situ Resource Utilization (ISRU). The lunar soil contains approximately 43% oxygen that is contained within the oxides of the lunar soil (Colozza and Wong, 2006). Extracting and processing this oxygen for consumption by astronauts or use in propulsion systems will significantly reduce the mass a spacecraft must transport from the Earth to the moon. Furthermore, lunar based oxygen production is an important step towards sustainable, Earth-independent habitation of the moon. Realizing this goal would be invaluable for further exploration of the solar system (Findiesen et al., 2008).

Production of oxygen is a batch process. Fresh regolith is added to a reactor, then heated up to 1050°C using roughly 4 kW of solar power. After the reactor is at 1050°C, hydrogen flows though the reactor, and reacts with the oxygen in the lunar regolith to produce water. The water is then electrolyzed to produce oxygen, and recycle the hydrogen into the process. During the oxygen production process, the reactor requires only about 1 kW of solar power to maintain the temperature. The mass of the overall system can be minimized if one solar concentrator supplies a constant rate of power to two reactors, with the power switched from one reactor to the other as fresh batches of regolith are added.

A Pressure Controlled Heat Pipe (PCHP) is a viable solution to utilize a single energy source to provide power and heat to two separate reactors; see Figure 9. The assumed base location is near the lunar South Pole, so the sunlight is always coming from near the horizon. The sunlight is focused with a solar concentrator that directs the solar energy down into the central Solar Receiver Heat Pipe (SRHP).

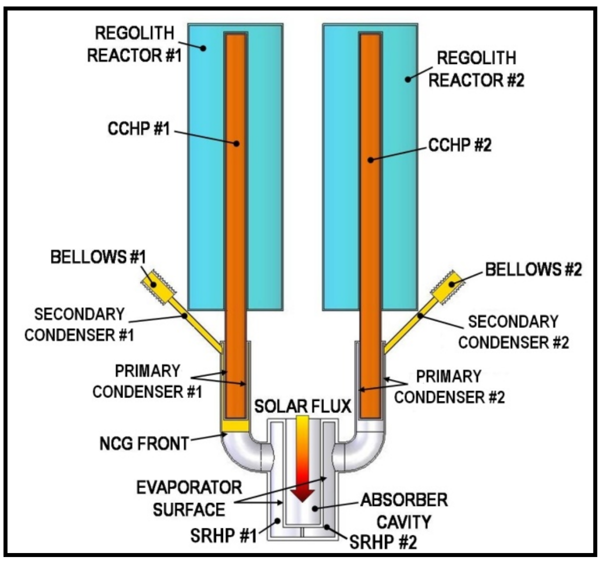


Figure 9. Schematic of the PCHPs and CCHPs used to transfer heat to the two reactors.

E. Lunar Regolith PCHP Operation

A single one-half scale regolith processing plant is designed to produce up to 500 kg of oxygen per year (Macosko et al., 2010). For the half scale plant, the initial thermal power to heat up a single batch of regolith is approximately 4.0 $kW_{thermal}$. 3.0kW of this amount is required to heat the regolith batch, and 1.0 kW_{th} is required to make up for thermal losses of the batch (at 1050ºC) to the environment, depending upon the insulation package design. To achieve near continuous regolith processing, dual processing reactors were used, where each will be operating out of phase. A projected operational scenario for the start up and operation of a multiple reactor system is as follows:

Step 1: Initially, 4kW of power would be put into the first reactor at startup. Step 2: The first reactor would reach 1050°C and 3kW is switched to heat up the second reactor. 1kW would be supplied to the first reactor for processing of the regolith. Step 3: At this time the second reactor would reach 1050°C and 2kW is switched back to the first reactor giving a total of 3kW to first reactor and 1kW to the second reactor. The spent regolith would need to be dumped and the reactor would be refilled during change-overs. The control of the thermal loading between multiple reactors, using a single solar receiver can be accomplished using Pressure-Controlled Heat Pipes (PCHPs). It is also necessary to either defocus the concentrator, or reject the excess power during reactor filling.

Thermal input can be provided by either nuclear or solar sources. This effort is focusing on a single solar source for thermal input. The solar concentrator design and location on the lunar surface define the direction of the solar flux and the associated heat pipe receiver orientation. For operation in the Shackleton Crater on the South Pole, the solar flux will be incident from the lunar horizon and will be directed downward into the opening of the solar receiver. As a result, the heat pipe solar receiver is positioned vertically with respect to lunar gravity. Further details about the operating sequence can be found in Hartenstine, et al. (2011).

F. PCHP for Lunar Regolith Design

The design and control scheme for the SRHP lunar regolith processing system are complex. For this reason, multiple demonstration systems were designed, fabricated and tested. The first two test systems were low-temperature while the remaining two were high temperature utilizing the same envelope materials and working fluids that would be used on the moon. A description of the four test systems follows:

1. Low-temperature, single-sided water/Monel system
2. Low-temperature, double-sided water/Monel system
3. High-temperature, single-sided alkali metal/Haynes 230 system
4. High-temperature, double-sided alkali metal/Haynes 230 system

1. Low Temperature System Design

The low-temperature, water/Monel systems are used to demonstrate the feasibility of the system and develop the control scheme without the complexity of using an alkali metal working fluid. The advantages of the water/Monel system include lower cost, ease of fabrication, and the ability to make changes to the system and recharge the heat pipe. The small scale demonstration systems are similar to the design of the full scale system; however, they are scaled down and carry roughly one-tenth of the full power. The low temperature system design and test results, and the single sided high temperature results can be found in Hartenstine, et al. (2011).

2. High Temperature System Design

The PCHP concept for using solar power to provide oxygen from lunar regolith is shown in Figure 9. The system components include:

1. Two Solar Receiver Heat Pipes (SRHPs), one for each regolith processing reactor.
2. Two Constant Conductance Heat Pipes (CCHPs), one for each reactor.
3. A primary condenser on each SRHP.
4. A secondary condenser on each SRHP, with bellows to vary the reservoir volumes.

The SRHPs are used to control the gas front location, and therefore control the power delivered to each reactor. The CCHP transfers the thermal load to the reactor from the variable conductance SRHP. CCHPs are used to provide uniform heating to the regolith. The change in the exposed length of the two condensers of each SRHP would vary as the power was transferred. The secondary condensers provide a method to reject excess heat, so that the concentrator can always deliver the full heat load to the SRHP.

The SRHP is divided into two halves that are thermally connected, with Non-Condensable Gas (NCG) added to each side. Each half has a side arm which serves as a primary condenser, a secondary condenser and a bellows. During steady-state operation, one reactor is gradually heating the regolith, while the other reactor is extracting oxygen. The bellows are used to control the location of the gas fronts on each side, and hence the heat supplied to each side. For example, assume that Reactor #2 is at 1050°C, with hydrogen flowing to extract oxygen from the regolith. Cold regolith is added to Reactor #1, and starts to warm up. The amount of heat added to Reactor #1 must be throttled, to prevent the temperature of the SRHP and Reactor #2 from dropping below 1050°C. As the regolith heats up, the gas front is gradually withdrawn, until both reactors are near 1050°C. At this point, excess heat from the solar concentrator is dissipated by radiation from the secondary condenser #1. Once Reactor #1 has been heated up, oxygen production is started. The regolith from Reactor #2 is then dumped and replenished. The secondary condensers are used to reject excess heat when necessary, so that the solar concentrator does not have to be defocused.

The high-temperature double-sided system is scaled down from the full-scale regolith system to allow operation with electrical heaters, rather than a solar concentrator. The full-scale design supplies 4kW of power between the two reactors; 3kW for warm up and 1kW for processing. The scaled down design provides 1.2kW for warm up and 400W for processing. The complete design requirements and capabilities for this design can be seen in Table 6.

Table 6. Haynes 230 final system requirements and capabilities.

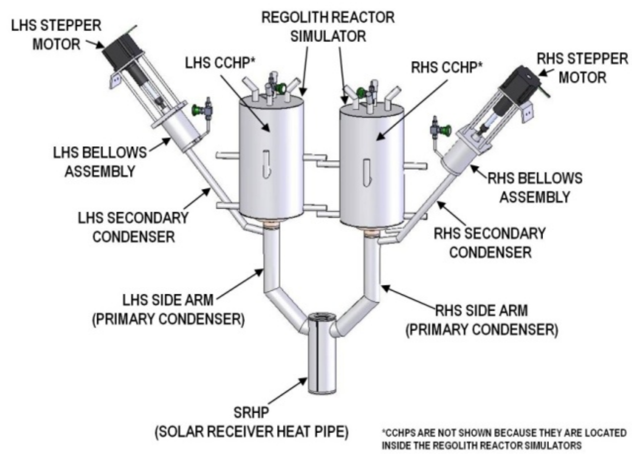
PARAMETER	VALUE
Operating Temperature	1050°C
Total Heat Losses*	1000W
Power Required for Warm Up	1200W
Power Required for Processing	400W
Power Input	2600W+

*Heat losses take into account 1inch of Microtherm Super A and 2inch of Microtherm Board Insulation

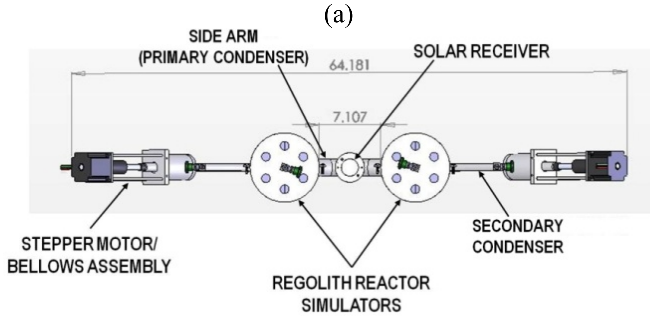
3. High Temperature System Fabrication

The high-temperature double-sided system has an annular SRHP split in two halves, each with its own side arm, CCHP, secondary condenser and bellows/stepper motor assembly; see Figure 10. The evaporator for the system is located on the exterior surface of the inner vertical pipe. Each SRHP has a separate evaporator, with the vapor space split into two halves by welding a thin Haynes 230 plate on the inside. This plate creates two separate vapor spaces for each side of the evaporator, isolating the NCG from each SRHP.

Heat input for the system was provided by a 1700 W Kanthal heater inserted into the solar receiving portion of the evaporator. In addition, supplemental heaters were installed at the base of the solar receiving portion of the evaporator to provide the remainder of the heat. The distance between the regolith reactor simulators that will be used for the double-sided Haynes 230 system can be seen in Figure 10. The final system (before insulation was added) is shown in Figure 11.



(a)



(b)

Figure 10. Final High-temperature Double-Sided Alkali Metal/Haynes 230 system. a) side view, b) top view.

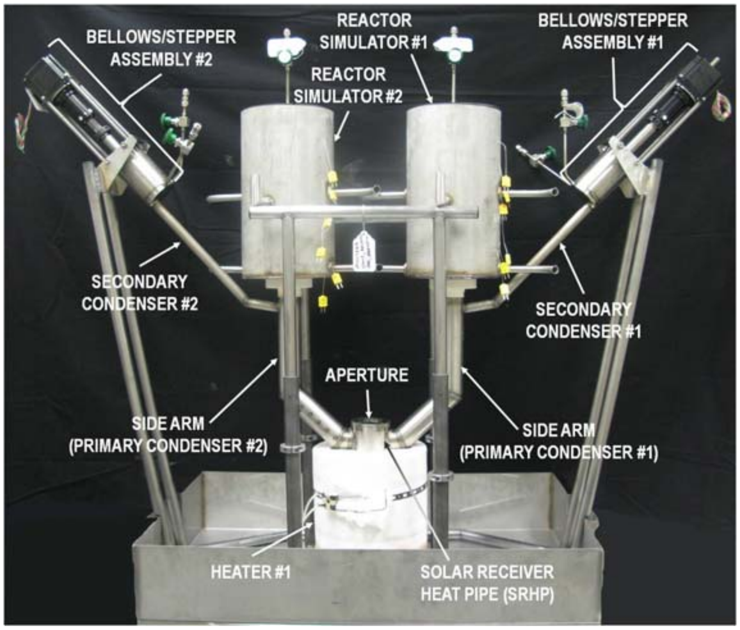


Figure 11. Dual sided Haynes 230 demonstration system test setup.

G. PCHP for Lunar Regolith Testing

4. Test Setup

Prior to testing, the side arms (primary condensers) were covered with 2 inches of Microtherm insulation. The vertical, annular portion of the system was insulated using the insulation package provided with the ceramic heater. Kaowool was also used as extra insulation and covered the entire system with the exception of the secondary condensers. The dual sided test setup is shown in Figure 12 including the thermocouple locations. The TC distribution is as follows:

- TCs 1 and 26 measure the vapor temperature in the evaporators of both sides of the system.
- TCs 2 through 4 and TCs 27 through 29 measure the vapor temperature in the adiabatic sections of the heat pipes.
- TCs 5 through 12 and TCs 30 through 37 measure the vapor temperature in the primary condenser where the evaporator of the CCHP is located.
- TCs 13 through 17 and TCs 38 through 42 measure the surface temperature in the secondary condensers.
- TCs 19 and 50 measure the vapor temperature of the CCHP condensers.
- TCs 18 and 43 measure the temperature of the bellows assemblies.
- TCs 20 through 25 and TCs 44 through 49 measure the temperature of the “regolith.”

The temperature of the “regolith” was measured intrusively by 6 TCs at equidistant locations along the vertical direction inside the “regolith” at the mid distance between the cylindrical case and the central axis. The average value was used to represent the “regolith” temperature.

5. Test Results

The total power between the two heaters was set to approximately 3.5kW, and was held constant for testing. This power represents the constant power the system would receive from a solar concentrator during actual operation. Figures 13 and 14 represent the transient behavior of the dual sided system during a dual cycle time period. The left hand side of the system can be found in Figure 13, the right hand side of the system can be found in Figure 14 and the sides operating together can be found in Figure 15. The left side of the system was operated through two full cycles (charging-processing-replenish represents one full cycle) while the right side was operated through one and a half cycles. Four temperatures are represented on the primary ordinate axis for each reactor:

- SRHP vapor temperature, TC1 & TC26
- Vapor temperature at the entrance of the secondary condenser, TC13 & TC38
- Vapor temperature in the CCHP condenser, TC19 & TC50 (indicates when NCG front enters the secondary condenser)
- Average "regolith" temperature

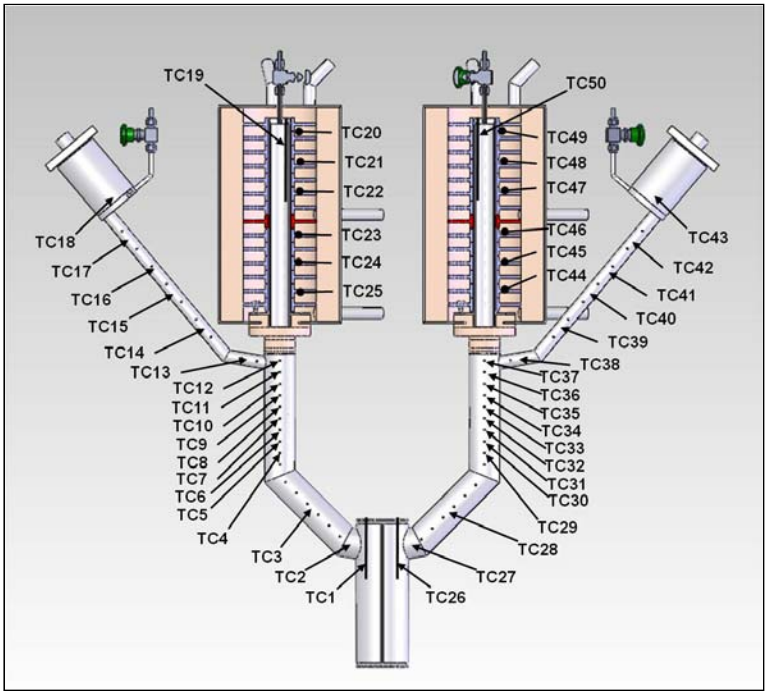


Figure 12. TC map for the dual sided Haynes 230 demonstration system.

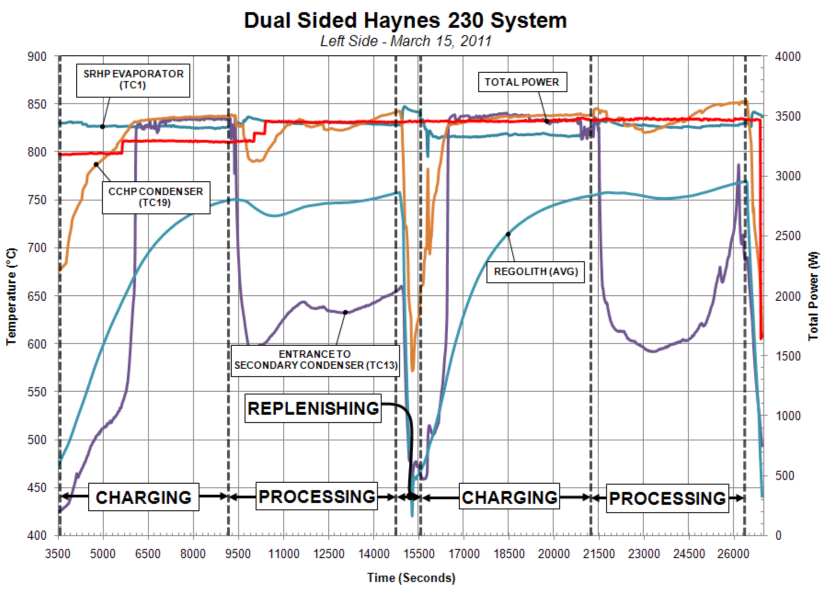


Figure 13. Dual sided Haynes 230 & sodium demonstration system - left side operation.

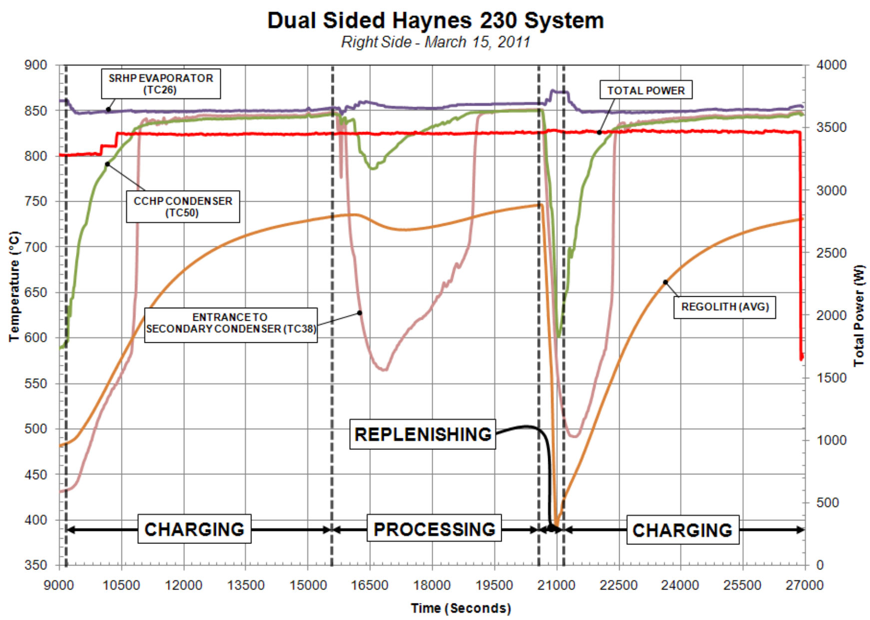


Figure 14. Dual sided Haynes 230 & sodium demonstration system - right side operation.

Testing of the dual sided system was conducted at lower temperatures then the nominal operating temperature of 1050°C. This decision was made to be conservative and protect the heaters from an over temperature condition. A lower operating temperature was also chosen due to the heat losses from the system. An operating temperature of 850°C was chosen. Testing of the dual sided system was performed manually: an automatic control program was not used. The vapor temperature of the SRHP evaporators was observed and the stepper motor was moved to maintain it at a constant value. In a charging state, the stepper motor was moved to pull the NCG into the bellows assembly. At the beginning of a processing state, the stepper motor was moved to push the NCG out of the bellows assembly and into the primary condenser. In the middle of the processing state, the NCG front should be moved to maintain the "regolith" temperature therefore the stepper motor was moved to either push or pull the NCG front. In a replenishment state, the stepper motor was moved to push the NCG out of the bellows assembly to blanket as much of the CCHP evaporator as possible.

The temperature set points were designated as follows:

- Regolith preheat temperature ~ 470°C
- SRHP vapor temperature ~ 850°C
- Regolith processing temperature ~ 750°C

As seen in the figures, the SRHP evaporator vapor temperature was maintained relatively constant for both sides through all stages of the cycle. A ΔT was experienced across the wall that separates the two SRHP vapor spaces. This temperature difference occurs as a result of the heat flux transmitted through the splitting plate from on evaporator to the other because of the unbalanced heat load through the two SRHPs. This ΔT was maintained at approximately 10°C during manual operation. . The first charging stage for both the left and right hand sides of the system took approximately 92 to 94 minutes. Charging for the second cycle took approximately 84 to 86 minutes. A ΔT of approximately 100°C was experienced for both sides between the CCHP vapor temperature and the average regolith temperature. The fluidized bed used in a true regolith reactor would greatly reduce this ΔT due to the higher effective thermal conductivity.

Soon after charging starts, a sharp increase in the secondary condenser temperature is experienced in TCs 13 and 38 for the left and right sides, respectively. This is due to the NCG front reaching the entrance of the secondary condenser and thus rejecting the excess power that cannot be conducted into the regolith. At this point in time the ΔT between the CCHP vapor temperature & SRHP vapor temperature is too small and the excess power must be rejected. This can be seen graphically as the CCHP vapor temperature at this moment has reached approximately 830°C for the left hand side and 840°C for the right side. A drastic drop in temperature is observed in the CCHP vapor, regolith and secondary condenser during the replenishment stage of the cycle. At this moment the forced air cooling systems for the regolith reactor simulator was turned on to simulate the removal of processed regolith and addition of new regolith.

The regolith temperature was maintained near constant for all processing cycles for both the left and right hand sides of the system. A slight dip in temperature is observed in both reactors during processing due to more power being transferred to the opposite side to aid in charging, which is the power heavy stage in the full cycle. To summarize, testing of the dual reactor system was completely successful.

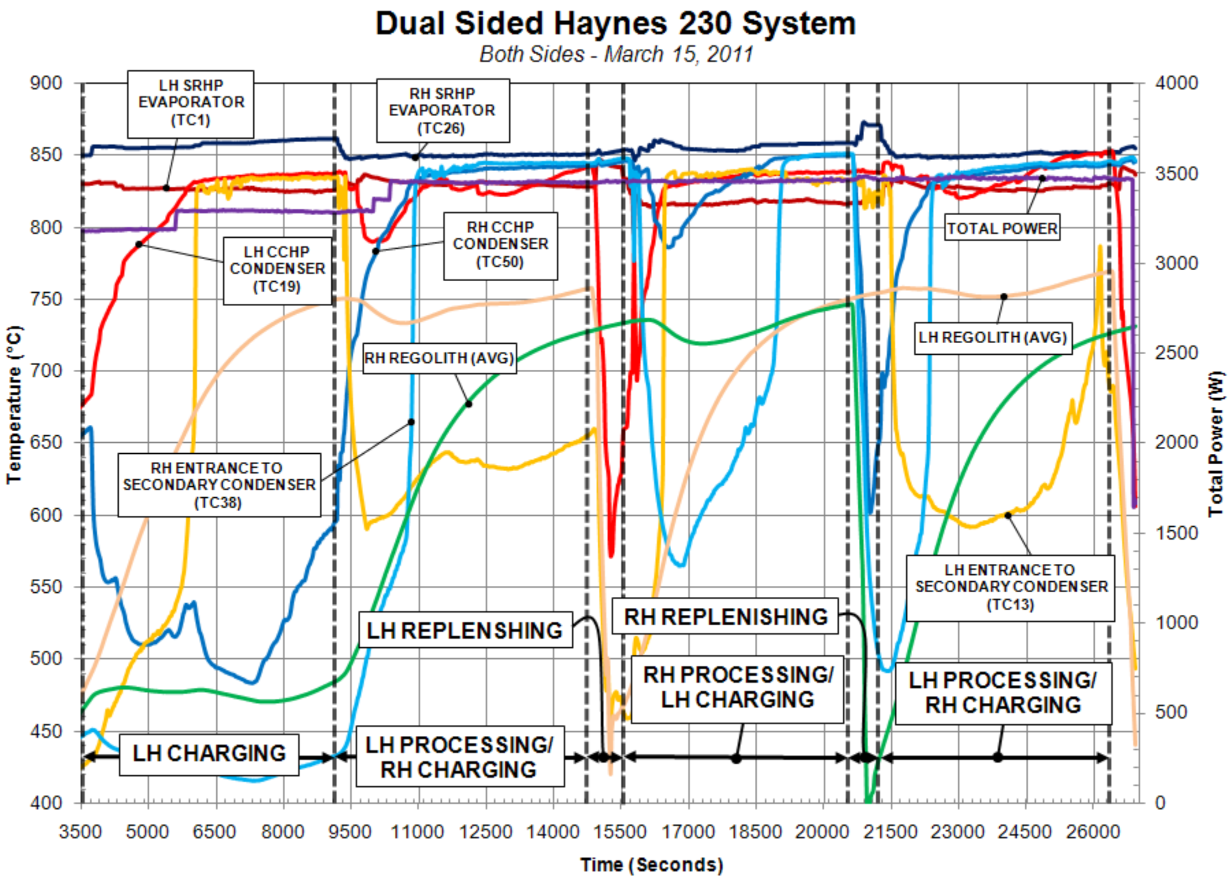


Figure 15. Dual sided Haynes 230 & sodium demonstration system - both sides operating.

Conclusions

Pressure controlled heat pipes are a variant of variable conductance heat pipes, where the amount or volume of NCG in the heat pipe can be adjusted for control of the thermal conductance. PCHPs can be used for precise temperature control at the milli-Kelvin level, and for switching power at high temperatures, where there are no known alternatives.

PCHPs for Precise Temperature Control

A series of aluminum/ammonia PCHPs and a propylene PCHP were fabricated that achieved good closed-loop feedback control. The ammonia PCHP was able to maintain a constant evaporator temperature over changes of input power from 50-150 Watts and changes of sink temperature from -10°C to -40°C. The ammonia PCHP met the goal of milli-Kelvin control, by demonstrating a standard deviation of 0.006K in evaporator temperature over time. The propylene PCHP demonstrated temperature stability over changes of input power from 10-60 Watts. The PCHP technology was brought to TRL-6, Prototype Demonstration in a Relevant Environment. A complete PCHP including motor and bellows were shown to operate well in a vacuum system and to have survived launch-like vibration loads with no change in performance. Supporting components such as suitable low-mass motor and a long-lived bellows were identified. Cycle testing of both the motor and bellows showed margins of between 4x and 50x over the design requirements of a ten-year life.

PCHPS for Power Switching

To summarize, methods to control the thermal loading from a single solar source to multiple lunar regolith oxygen processing reactors were investigated using a thermal management system including PCHPs and CCHPs. Thermal energy was introduced into the aperture of a Haynes 230/sodium heat pipe operating at 1050ºC. This temperature must be maintained to efficiently process oxygen from lunar regolith using the hydrogen reduction process. The sodium heat pipe was a PCHP with an integral CCHP. The amount of thermal energy was adjusted between multiple reactors by varying the volume of non-condensable gas (NCG) in the PCHP using a bellows or piston and stepper motor.

Two low-temperature, smaller scale systems were designed and fabricated using Monel/water heat pipes to understand performance characteristics and NCG control prior to using alkali metals. Preliminary testing indicates that the NCG can be controlled to effectively throttle the thermal load to the CCHP and the lunar regolith.

Two high temperature, scaled down systems were designed, fabricated and tested using a Haynes 230/sodium heat pipe system to understand performance characteristics & NCG control at elevated temperatures. The dual sided Haynes 230/sodium demonstration system was fabricated with Haynes 230 as the envelope, sodium as the working fluid and argon as the non condensable gas. Two full cycles were demonstrated on the left hand side of the system and one and a half cycles were demonstrated for the right hand side. The power input to the system was held constant throughout testing. The dual sided system was successful in demonstrating the ability to utilize a single heat source to transfer power between two separate reactors that are operating out of phase with one another.

Acronyms

CCHP, Constant Conductance Heat Pipe
ISRU, In-situ Resource Utilization
LHP, Loop Heat Pipe
LHS, Left Hand Side
NCG, Non-Condensable Gas
PCHP, Pressure Controlled Heat Pipe
RHS, Right Hand Side
RTD, Resistance Temperature Detector
SRHP, Solar Receiver Heat Pipe
TC, Thermocouple
VCHP, Variable Conductance Heat Pipe

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