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Low-Temperature, Dual Pressure Controlled Heat Pipes for Oxygen Production from Lunar Regolith

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ABSTRACT

Oxygen can be extracted from lunar soil by hydrogen reduction: the lunar regolith is heated using a solar concentrator to approximately 1050°C and exposed to hydrogen gas. Water is formed from the reaction and the oxygen is recovered by electrolysis of the water. To minimize mass, it is desirable for the solar concentrator to supply heat to more than one reactor. In a dual reactor system, one reactor is at 1050°C extracting oxygen. The second reactor, filled with fresh, cold regolith, uses the majority of the solar power to heat the regolith up to the extraction temperature. After one hour, the roles of the reactors switch, and the fraction of power supplied to each reactor must be switched. A method has been developed using Pressure Controlled Heat Pipes (PCHPs) to shuttle the solar power from one reactor to the other. The final system will use sodium as the working fluid, with a Haynes 230 envelope material. This paper reports on the design and testing of two lower temperature Monel/water systems that have been used to verify the performance and control scheme for the overall design.

KEY WORDS: Pressure Controlled Heat Pipe, PCHP, Variable Conductance Heat Pipe, VCHP, Oxygen Production from Lunar Regolith

1. OXYGEN PRODUCTION FROM LUNAR REGOLITH

Oxygen from lunar regolith can be extracted to provide breathable oxygen for consumption by astronauts during long term stays on the Moon. The regolith is heated using concentrated solar energy to 1050°C, and then hydrogen is introduced that reacts with the regolith, extracting oxygen in the form of water vapor. After several hours, the regolith is dumped, and fresh regolith is added.

To minimize mass, it is desirable to supply thermal energy to multiple reactors with a single concentrator. This paper discusses a system that uses Pressure Controlled Heat Pipes (PCHPs) to transfer heat to the two reactors.

2. PCHPS FOR REGOLITH PROCESSING

A Variable Conductance Heat Pipe (VCHP) is typically used in spacecraft thermal control to provide relatively tight temperature control to an instrument. A reservoir filled with Non-Condensable Gas (NCG) is attached to the condenser end of a heat pipe. A heater is attached to the reservoir. Heating the reservoir forces more NCG into the condenser, partially blocking the condenser. Allowing the reservoir to cool reduces the blockage. The heat pipe evaporator temperature can be controlled, typically to ±1-2°C, by controlling the reservoir temperature.

Pressure controlled heat pipes can be used when more precise temperature control is required. In a PCHP, gas is added/subtracted from the reservoir, or the reservoir volume is changed. This method was first used for precise temperature control in isothermal furnace liners. Gas was added from a bottle as required, and removed with a vacuum pump (ACT, 2010). This type of system is suitable for ground-based applications.

More recently, Sarraf and co-workers (Sarraf et al., 2008, 2009) have developed an aluminum/ammonia PCHP suitable for spacecraft applications. This PCHP uses a bellows, so the system is completely sealed. The evaporator temperature can be controlled to within 8 mK with varying powers and sink conditions.

This paper describes a different application for PCHPs. Instead of precise temperature control, multiple PCHPs are used to shuttle power between different reactors.

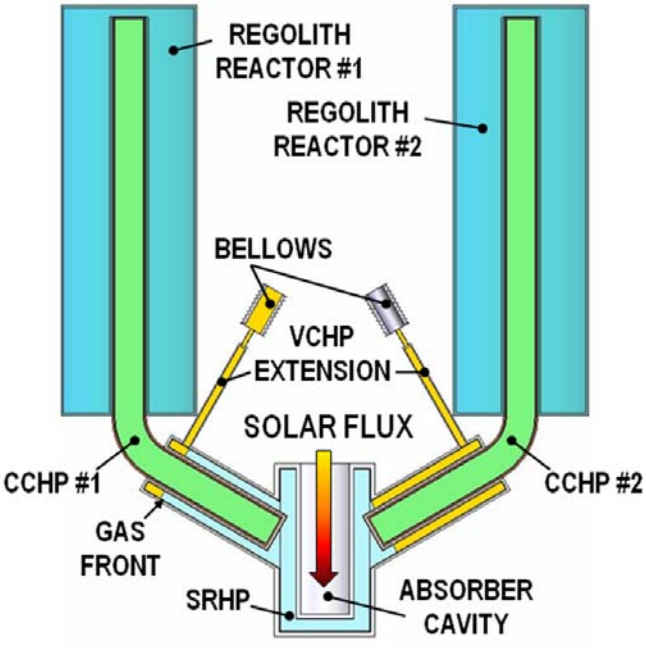

Figure 1. Schematic of the PCHPs and CCHPs used to transfer heat to the two reactors.

2.1 PCHP Cycle

A Pressure Controlled Heat Pipe (PCHP) solar receiver is under development to accept, isothermalize and transfer the solar thermal energy to multiple reactors for oxygen production. As shown in Figure 1, the receiver has a central Solar Receiver Heat Pipe (SRHP) and a Constant Conductance Heat Pipe (CCHP) for each regolith reactor.

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 with a VCHP extension 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 #1 is at 1050°C, with hydrogen flowing to extract oxygen from the regolith. Cold regolith is added to Reactor #2, and starts to warm up. The amount of heat added to Reactor #2 must be throttled, to prevent the temperature of the SRHP and Reactor #1 from dropping below 1050°C. As shown in Figure 1, the bellows is used to block almost all of the CCHP #2 evaporator with NCG. 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 VCHP extensions. Once Reactor #2 has been heated up, oxygen production is started from it. The regolith from reactor #1 is then dumped and replenished. The VCHP extensions are used to dump excess heat when necessary, so that it is not necessary to defocus the solar concentrator.

2.2 Experimental Systems

The design and control scheme for the SRHP lunar regolith processing system are complex. For this reason, four separate devices will be fabricated and tested:

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.

The low-temperature, Water/Monel systems are used to demonstrate 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, carrying roughly one-tenth of the full power.

3. SINGLE-SIDED LOW TEMPERATURE SYSTEM

The single-sided Monel/water demonstration system can be seen in Figure 2. The components of the system include:

- Solar receiver heat pipe (SRHP)
- Constant conductance heat pipe (CCHP)
- Heater block
- Aluminum thermal mass (to simulate the cold regolith)
- VCHP extension (with attached fins to dissipate the heat through forced convection)
- Piston
- Stepper motor

The operating temperatures for the system ranged from a minimum of 20°C to a maximum of 120°C with an operating power of approximately 300W. The small-scale demonstration consists of one-half of the full scale system; one SRHP and one CCHP.

The vertical, solar flux receiving portion of the solar receiver heat pipe was removed from the small scale demonstration to also aid in simplifying the system. A heater block was used to simulate the solar flux that the real system would receive from the solar concentrator. Cartridge heaters inserted into the heater block provided the thermal power for the system. An aluminum thermal mass was used to simulate the cold regolith that will be used in the real system. Liquid nitrogen was used as the mechanism of cooling the thermal mass. Fins were added to the VCHP extension and a fan was used to generate forced convection to dissipate excess thermal power. A stepper motor and a piston were used to adjust the NCG front location. Detailed dimensions are given in Hartenstine et al. (2010).

As shown in Figure 3, the Monel and water system was equipped with a total of 35 thermocouples (TCs): 25 spot welded to the outer surface of the heat pipes, 3 vapor well TC's in the SHRP evaporator and condenser, and CCHP condenser, and spring loaded TC's in the heater and condenser blocks. The TCs track the NCG front in incremental locations. A small change in piston location could result in a much larger change in the location of the NCG front and it was important to have a high linear temperature resolution in the SRHP condenser to be able to track these changes.

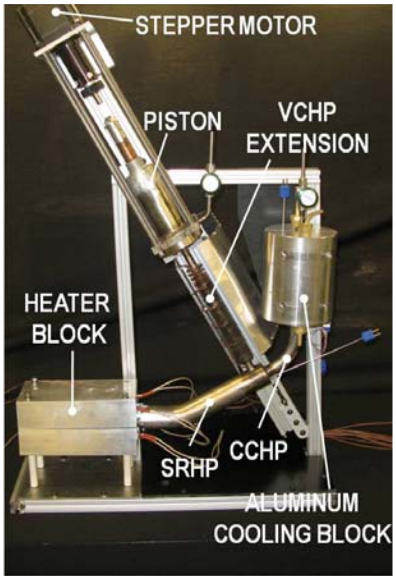

Figure 2. Single-Sided Monel/Water System.

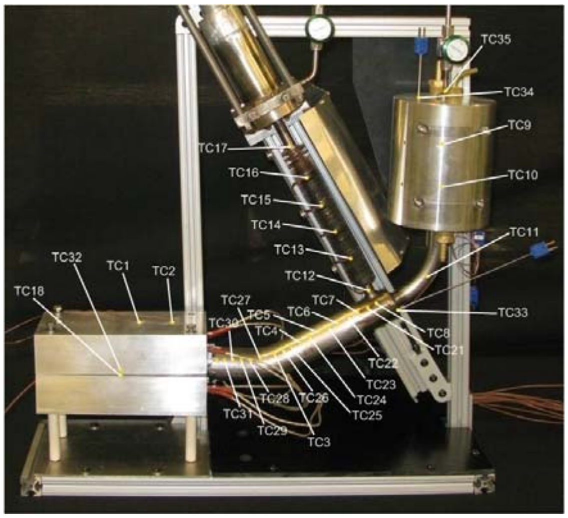

Figure 3. Thermocouple locations for the single-sided water/Monel system.

3.1 Single-Sided Test Procedure

For the full-scale high temperature system the processing temperature for the regolith will be 1050°C; however, for the small scale demonstration unit the actual value is arbitrary so it was chosen as 120°C. After the regolith, or in this case the aluminum thermal mass representing the lunar regolith, has reached the processing temperature, the power will be transferred from one side of the system to the other to aid in “heat up” of the second regolith reactor. For the demonstration unit the transfer of power from one side to the next was represented by simply decreasing the power being provided to the system from 300W to 50W. The regolith reactor will process the lunar regolith for approximately 1 hour in the full-scale system. For the demonstration unit, the time to process was arbitrary and was chosen as anywhere from 30 to 45 minutes. After processing, the lunar regolith is dumped and new lunar regolith is added. This was represented in the demonstration unit by turning on the liquid nitrogen being provided to the thermal mass with a set point of 20°C. Once the thermal mass reached the set point, the LN was turned off, signaling the start of another “heat up” process. The piston and the associated gas front position was controlled using the SRHP evaporator temperature. Changes in the CCHP condenser temperature, simulating regolith load, process and replenish, result in changes in the evaporator temperature and the associated NCG gas front.

3.2 Single-Sided Test Results

The results from testing can be seen in Figure 4. It shows the temperature and power as a function of time during 3 cycles. Five representative TCs were chosen for this figure for clarity in the graph. The temperatures plotted were the SRHP evaporator vapor temperature, the SRHP condenser vapor temperature, the CCHP condenser vapor temperature, the SRHP condenser temperature at the inlet of the VCHP extension (surface mount) and the SRHP condenser temperature at approximately the middle of the SRHP condenser (surface mount).

The control scheme maintains an approximate evaporator temperature of 120°C regardless of the amount of power the system is being provided. The SRHP condenser temperature is maintained at approximately the same temperature as the SRHP evaporator. The temperature of TC 23 stays at approximately the same temperature as the SRHP evaporator and condenser. This shows that the NCG front is not located at these particular points. TC 8, located at the inlet of the VCHP extension, fluctuates from approximately 40 to 110°C during operation. This shows that the NCG front is indeed blanketing the CCHP evaporator at the low temperature points, preventing the thermal load from transferring to the CCHP. This is also evident by the fluctuation in the CCHP condenser from approximately 40 to 100°C. For the given operating conditions, it would be more ideal for the CCHP condenser temperature to range from 20 to 120°C; however this plot shows that the PCHP design is effectively shutting off power from being transferred to the CCHP and the regolith block while still maintaining the 120°C temperature in the evaporator regardless of the amount of power being provided or the sink conditions. Further modifications will need to be made to the operating program for the piston to improve the temperature range experienced in the CCHP condenser.

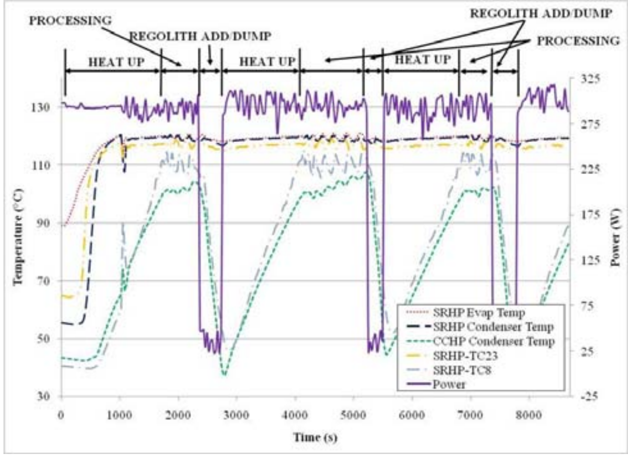

Figure 4. Power and Temperature Plots during Cycling Testing of Monel and Water Demonstration System

4. DOUBLE-SIDED LOW TEMPERATURE SYSTEM

The second, low-temperature double sided water/Monel system can be seen in Figure 5. The final system consists of:

- One shared heater block
- Two SRHPs
- Two CCHPs
- Two aluminum regolith simulators
- Two piston and stepper motor assemblies (includes stepper motor, piston and stepper motor controller)
- Two VCHP extensions

The test system was outfitted with 61 TCs total; however, for the sake of clarity when generating figures, only 6 TCs are shown. The 6 TCs of most importance are the left hand and right hand evaporator temperatures, the left hand and right hand CCHP temperatures and the left hand and right hand regolith temperatures. The location of these 6 TCs can be seen in Figure 6.

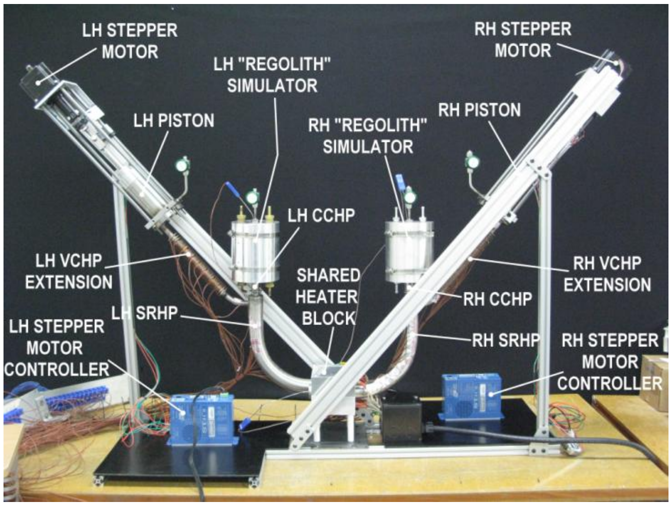

Figure 5. Double-sided Monel/Water System.

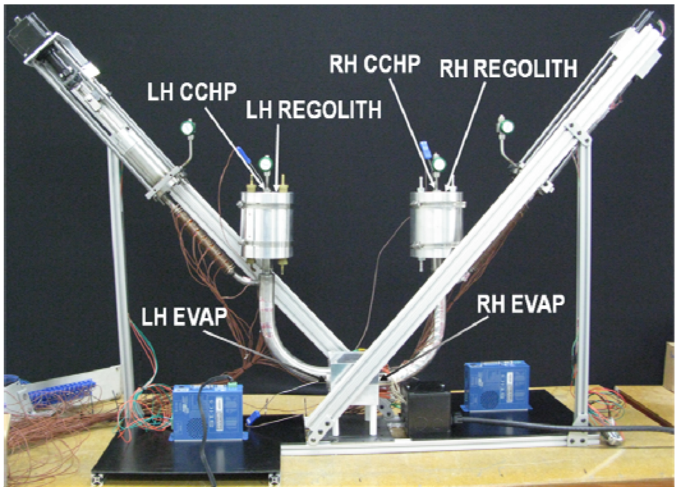

Figure 6. Location of the six thermocouples shown in Figure 7.

4.1 Double-Sided Test Results

A preliminary test for the double-sided PCHP is shown in Figure 7. As seen in the figure, the left hand side (LHS) warms up in a little under an hour and then processes at approximately 110°C for an hour. When the LHS begins processing the right hand side (RHS) begins its warm up cycle. When the LHS completes processing the RHS should be entering its processing stage. As seen in the test results, the LHS warmed up quicker than the RHS. The LN was turned off for the LHS during processing (as noted by the gradual decrease in temperature at the end of the LHS processing cycles) to allow the RHS to continue to warm up. It was observed during the RHS process that the “regolith” reached the desired processing temperature, but instead of holding that temperature it began to gradually decrease. This was observed for all processing cycles for the RHS, even after the power was increased mid-way through increased during testing. This increase in power can be observed during the second RHS processing cycle. The temperature gradually decreased, but then began to increase about mid way through the processing cycle.

We believe that the issue with one side not holding the processing temperature occurs because the two evaporators are not closely coupled enough. The two sides of the system have separate evaporators that are joined by a shared heater block. They do not share a common evaporator vapor space and it was observed during testing that the temperature of either evaporator heavily influences the temperature of the opposite evaporator. The heater block will be redesigned to improve performance

5. CONCLUSIONS

Methods to control the thermal loading from a single solar source to multiple lunar regolith oxygen processing reactors are being investigated using a thermal management system including Pressure Controlled Heat Pipes and Constant Conductance Heat Pipes. Thermal energy is 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 is a PCHP with an integral CCHP. The amount of thermal energy is adjusted between multiple reactors by varying the volume of non-condensable gas (NCG) in the PCHP using a bellows or piston and stepper motor.

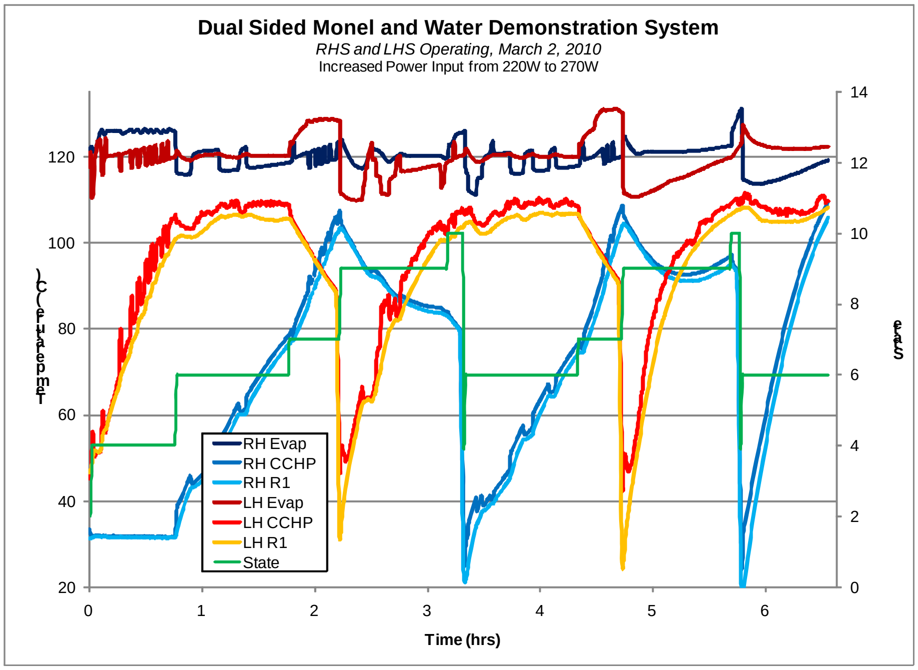

Figure 7. Dual Sided Monel and Water Demonstration System Test Results.

Two low-temperature, smaller scale system have been designed and fabricated using a Monel/water heat pipe system 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.

The next step is to build a high temperature, single-sided system. The heat pipes will be fabricated from Haynes 230, use sodium as the working fluid, and operate at 1050°C. This system will be used to test the high temperature bellows that will be required. The final system will be a dual-sided, Haynes 230 /sodium system operating at 1050°C.

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