Regolith Heat Recuperation with A Dusty Gas Heat Exchanger.

Ariane Chepko and Paul Sorensen, Creare Inc., 16 Great Hollow Road, Hanover, NH-03748, USA.

Introduction: Many methods for ISRU oxygen extraction process compounds from planetary or lunar regolith by heating the material to high temperatures in a batch processing mode. The energy may be supplied by solar collectors or from nuclear thermal energy; in either case, energy efficiency is essential for a viable system. Our novel heat exchanger is able to recover an estimated 80% of the heat in the spent reactant and transfer it to a fresh reactant batch prior to insertion into the reactor. The counter-flow heat exchanger for this application leverages the recent adoption of pneumatic regolith feed systems in NASA's oxygen extraction plant design. In an ongoing feasibility study, we are exploring heat transfer properties of gas suspended regolith and designing a prototype heat exchanger.

Heat exchanger design: NASA's baseline next-generation oxygen production plant design uses the reactant gas to pneumatically convey regolith from an inlet hopper to an annular chamber encasing the reaction chamber. Heating of the annular batch can occur from the heat leak through the core chamber of the hot, processed batch; however, the maximum possible recuperation in this configuration is 50% without accounting for any losses or heat transfer time constraints [1]. A counter-flow heat exchanger placed inline with the conveying system will transfer heat between dusty gas streams, taking advantage of the turbulent convection and mixing characteristics of a two-phase gas-particle suspension. This approach will enable much higher heat transfer rates than seen with conduction in a poorly conducting regolith solid, and in a counter-flow configuration, it is reasonable to achieve 80% heat exchange effectiveness.

For a hydrogen reduction oxygen production system, hydrogen gas is used to convey the incoming batch of regolith at ~0°C through the heat exchanger to a holding container (such as the annular reactor chamber). At the same time, hot, spent regolith at ~1000°C is conveyed in a hydrogen gas stream from the core reaction chamber, through the heat exchanger, and deposited in an outlet hopper where it can be transported by a rover to a waste pile. This would result in pre-heating the incoming regolith to 800°C and cooling the hot regolith to 200°C. Once the core reaction chamber is emptied, the pre-heated regolith can be transferred from the annular chamber to the reacting chamber. In a multi-reactor configuration, the annular holding container can become another reaction chamber operating in opposite phases such that one conveying step is eliminated. If an 80% effectiveness can be achieved, it can lead to an overall system energy savings of greater than 40%,[2] resulting in mass savings in the power plant.

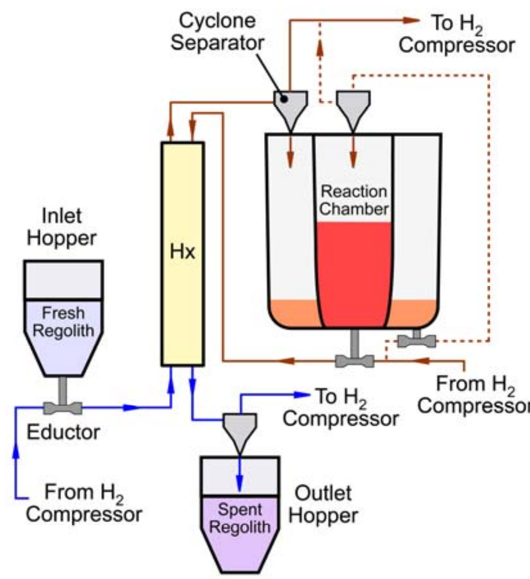

Figure 1. Regolith transfer and heat exchanger system schematic for in-situ resource extraction.

Using the reactor sizing reported by Linne [2] for a 1000 kg/year oxygen plant as a guideline, an approximate reactor height (and thus conveyance height) is on the order of 1 m. To achieve efficient packaging and reduce compressor conveyance power, a minimal heat exchanger length is desired. The primary factors in determining the required heat exchanger area are the gas Reynolds number, pipe diameter, and the loading ratio of solids in the gas stream. Higher mass flow rates increase the heat capacity of the flow stream and decrease the residence time in the heat exchanger, requiring longer heat exchangers to reach the desired effectiveness (80%). Adding solids to a gas stream can increase the heat transfer coefficient, an effect that varies depending on particle size and properties. To reach a high effectiveness in the heat exchanger with a minimal exchange area, the increase in heat transfer coefficient with higher loading ratios is balanced by the increased heat capacity of the flow stream. This effect can be seen in Figure 2 where for a given gas flow rate, the optimal loading ratio is approximately 1.2. To remain within transfer time, compressor power, and length constraints, a multi-tube heat exchanger design will be explored.

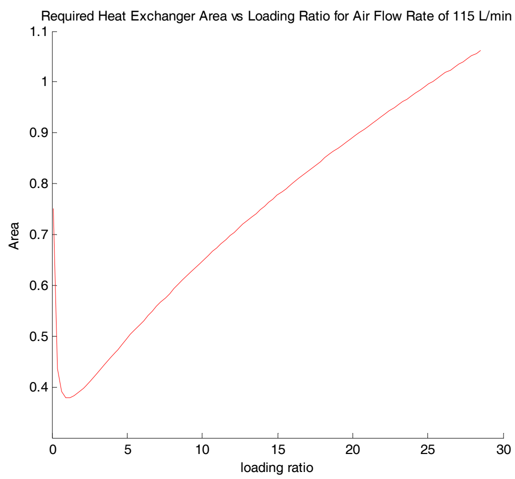

Figure 2. Heat Exchanger Area as a Function of the Loading Ratio of Solids.

Heat transfer testing: To determine feasibility of the dusty-gas heat exchanger concept, testing has begun to verify the heat transfer correlations for solid-gas flow streams. The test set-up consists of a single 0.5 inch diameter tube with a 1 meter long heated section. Lunar regolith simulant is conveyed in an air stream and the resulting temperatures measured.

At an air flow rate of 115 L/min and a loading ratio of 1.2, the measured heat transfer coefficient was 86 W/m^2K. This matches well with model predictions of 120 W/m^2K. In a counter-flow arrangement with a single tube per flow stream, a 9m length would be needed to achieve the 800C temperature increase in a full system. Because pneumatic conveying introduces abrasion and pressure drop concerns, many usual approaches to increase heat exchanger transfer area are not applicable. A 9m length can be accomplished by splitting the slow into multiple lines. Area enhancing features such as axial fins and corrugated tubing can also be incorporated to increase area without increasing the overall length. Figure 3 illustrates a feasible heat exchanger design concept.

Further testing at varying loading ratios and gas flow rates is underway to verify optimal heat transfer conditions. Flow tests will also be performed to determine the most effective area-enhancement strategies. The experimental data will feed into more detailed design models for a full-scale system. Initial test data supports our design models and demonstrates that heat recuperation during pneumatic regolith transfer can result in energy savings for the overall oxygen production system.

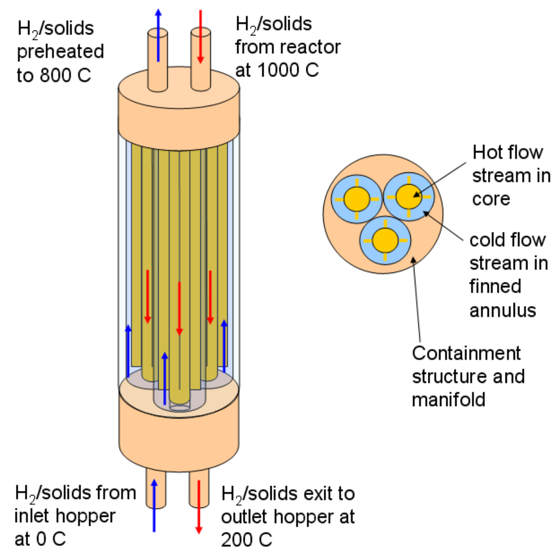

Figure 3 Preliminary counter-flow heat exchanger design. Overall length for this heat exchanger is 1 m.

References:

[1] Mueller, R., Townsend, I., Mantovani, J., Metzger, P., "Evolution of Regolith Feed Systems for Lunar ISRU O2 Production Plants," 48th AIAA Aerospace Sciences Meeting, 4–7 Jan 2010, Orlando, FL.

[2] Linne, D., "Employing ISRU Models to Improve Hardware Design," 48th AIAA Aerospace Sciences Meeting, 4–7 Jan 2010, Orlando, FL.