Modeling of JSC-1A Lunar Simulant Flow and Heat Transfer in the Helium Extraction & Acquiistion Testbed

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Introduction: The Helium Extraction and Acquisition Testbed (HEAT) is a laboratory prototype volatiles extraction system constructed to demonstrate a process for acquiring solar wind volatiles such as helium-3 (^{3}He) from lunar regolith. The ^{3}He could be used to fuel future fusion power plants that would produce little to no radioactive waste and efficient rockets for Solar System travel [1], [2]. Hydrogen, helium-4, carbon dioxide, carbon monoxide, methane, nitrogen, and water (from hydrogen reduction of ilmenite) are also products of the process. These volatiles could be very important in supporting the propellant and/or life support needs of people in space (space stations, lunar outposts, Martian outposts) for extended periods of time [3]. In the present research, helium is implanted into <100 µm JSC-1A regolith simulant using a device called the Solar Wind Implanter (SWIM). The HEAT system is used to extract up to ~50% of them by heating the material to 450 °C within a heat pipe heat exchanger. In this paper, key aspects of the flow and heat transfer modeling for the HEAT device are presented along with the modeling results.

Helium extraction & acquisition testbed design: The Helium Extraction & Acquisition Testbed (HEAT) is an experimental lunar volatiles extraction system designed to bring recuperative heat pipe heat exchanger (HPHX) technology for regolith to a Technology Readiness Level of 4 [4]. Figure 1 illustrates the concept of the HEAT project and a model of the HEAT hardware inside of a vacuum chamber. The components of the HEAT system are designed to control the inlet and outlet flow of regolith simulant through a HPHX, as illustrated in .

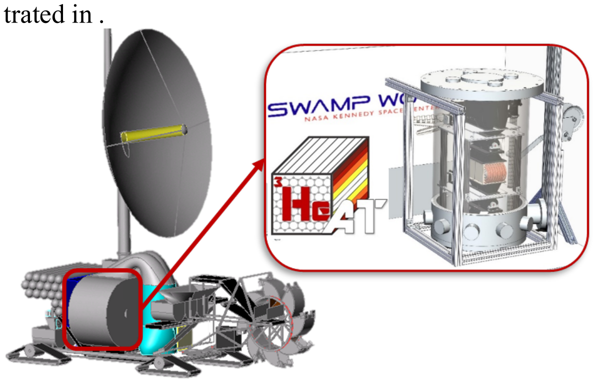


Figure 1. The HEAT system is a testbed for heat exchanger technology for lunar solar wind volatiles systems like the Mark-3 Miner (miner credit: Gajda 2006[5])

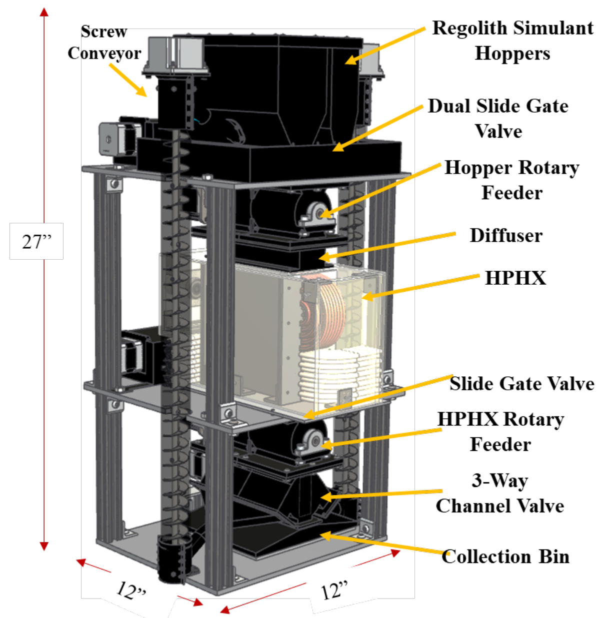


Figure 2. HEAT system components

JSC-1A simulant flow and heat transfer modeling
A standard heat pipe heat exchanger design approach, used in industrial multi-stage heat pipe heat exchangers, is used for the modeling of the HEAT system [6]. The heat transfer coefficients used in this modeling approach heavily depend upon the flow patterns of the heat transfer fluid passing over the heat pipes, <100 µm JSC-1A regolith simulant in this case. The modeling of the flow patterns is based on an approach developed and validated by Niegsch, illustrated in Figure 3, that takes into account the stagnation and void zones that develop due to the frictional properties of granular materials [7].

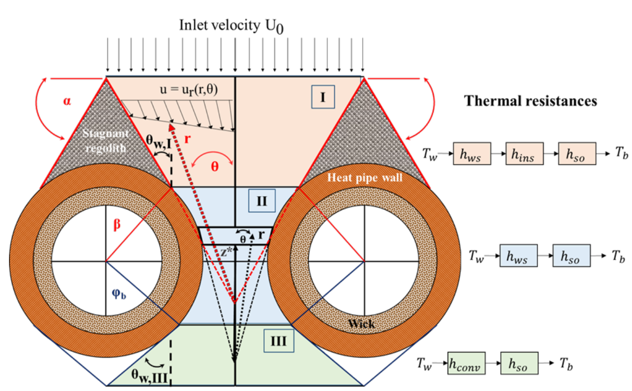
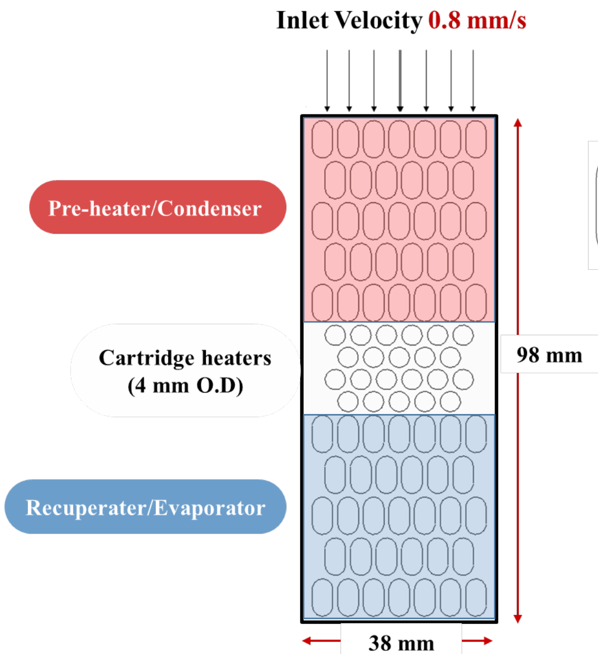


Figure 3. Three section flow channel between adjacent pipes and the sectional thermal resistances (adapted from Niegsch et al.)

The nominal HEAT HPHX was designed to be a cost-effective proof of principle system that fit within laboratory geometry constraints. The nominal HPHX configuration for extracting 50% of helium from 7 g/s of processed JSC-1A simulant is shown in Figure 4.



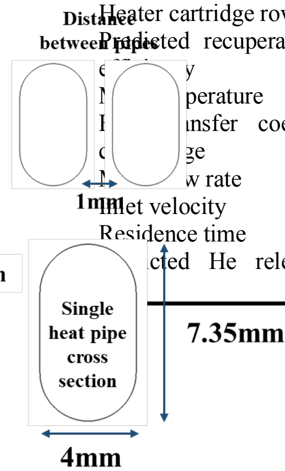


Figure 4. Illustration of the heat pipe heat exchanger configuration for the HEAT system using 5 rows of flattened 6 mm heat pipes and 4 rows of 4 mm O.D. cartridge heaters in a staggered 1 mm column spacing arrangement. The actual HEAT copper heat pipes are shown to the right.

Table 1. Parameters of the HEAT heat pipe heat exchanger, as illustrated in

Figure 4

Parameters	*Values*
Heat pipe columns	Three of 7, Two of 6
Heat pipe rows	Five
Heat pipe shape	7.35 mm x 4 mm (flattened 6 mm O.D. pipe)
Heater columns	Two of 6, Two of 5
Heater cartridge rows	Four
Predicted recuperative e[illegible]y	71%
M[illegible]perature	723 [K]
H[illegible]nsfer coeffi-c[illegible]ge	196 - 577 [W/m^2-K]
M[illegible]w rate	7 [g/s]
Inlet velocity	0.8 [mm/s]
Residence time	78 [s]
[illegible]cted He release	0.14 [μg/s]

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Fuel," *Fusion Technol.*, vol. 21, pp. 2230–2253, 1992. [3] P. T. Metzger, A. Muscatello, R. P. Mueller, and J. Mantovani, "Affordable, Rapid Bootstrapping of the Space Industry and Solar System Civilization," *J. Aerosp. Eng.*, vol. 26, no. 1, pp. 18–29, Jan. 2013. [4] A. D. S. Olson, J. F. Santarius, and G. L. Kulcinski, "Design of a Lunar Solar Wind Volatiles Extraction System," in *AIAA SPACE 2014 Conference and Exposition*, 2014. [5] M. Gajda, "A Lunar Volatiles Miner," University of Wisconsin-Madison, M.S. Thesis, 2006. [6] C. Silverstein, "Heat Pipe Heat Exchangers," in *Design and Technology of Heat Pipes for Cooling and Heat Exchange*, Philadelphia: Taylor and Francis Ltd., 1992, pp. 221–246. [7] J. Niegsch, D. Koneke, and P. M. Weinspach, "Heat transfer and flow of bulk solids in a moving bed," *Chem. Eng. Process.*, vol. 33, pp. 73–89, 1994.

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