Accurate modelling of ISRU technologies by CFD and DEM

Mart Heitkamp[1*] Luca Kiewiet[1]

[1]German Aerospace Center (DLR), Institute of Space Systems, Bremen, Germany
*mart.heitkamp@dlr.de

INTRODUCTION

Effective thermal management is crucial for In-Situ Resource Utilization (ISRU) technologies that aim to extract Lunar resources, such as water. Overcoming the latent heat of water is essential for the sublimation process. Heat within the Lunar regolith and ice mixture is transferred through conduction, advection, and radiation. Conduction arises from particle interactions in the mixture, while advective heat is facilitated by the gaseous phase of water. Radiation is transferred through the mixture from the application and solid particles. Upon the full sublimation of water within the Lunar regolith, outgassing is necessary before capture. Vapour molecules move through the regolith's pores, like gas flow in low-pressure microchannels. Advection occurs when high-pressure values are present in the void spaces, and this specific flow can be described using Darcy's law. Following outgassing, water vapour moves towards the system's open boundary. In ultra-high vacuum conditions, molecular interactions are minimal, prevailing molecular flow. When water exits the system, it remains in vapour phase. To convert it into consumable water for astronauts, the transition from gas to liquid or gas to solid to liquid must occur. Previous research has revealed minor sublimation rates caused by the poor thermal properties of Lunar regolith [1]. By accurate modelling of a rotating bed of Lunar regolith, these poor thermal properties can be enhanced. This study will be used for validation of LUWEX's experimental phase and further research development [2].

Variable		Value	Unit	Notes
rpm	Rotations per minute, a smooth step function from 0 to **rpm**	3	1/min	Transition required due to dense mixture
m	Mass of the icy-regolith mixture, where its bulk density is $\rho_0 = 1800$ kg/m^3	18.9	kg	Pore filling fraction of the mixture is 0.26
$\mathbf{T_1}$	[a]Temperature applied at the rods; a smooth step function transitioning from $\mathbf{T_i}$ to $\mathbf{T_1}$	273 - 373	K	See fluxes in fig. 2
$\mathbf{d_p}$	Particle size of regolith, where its particle density is 3240 kg/m^3	10-1000	µm	Porosity of 0.49
µ	Dynamic viscosity of water vapour	$1.7{\cdot}10^{-5}$	Pa·s	Important parameters for DEM
$\mathbf{T_i}$	Initial temperature	110	K	See red domain in fig. 1
ρ	Density of water vapour following the sublimation curve using the Ideal Gas Law	$\rho = P_S M/RT$	kg/m^3	Corrected with inital ice ratio in the sample
$\mathbf{P_S}$	Sublimation pressure as function of temperature in the system	P_S = **exp**(9.55-5723.27/T + 3.53logT– 0.00728T)	Pa	By Murphy and Koop [3]

Table 1: Current model parameters; future work involves sweeping all variables; [a]Experiments show a 10 min transition from 110 K to 373 K for current heaters w.r.t. the outer surface.

DESIGN & METHODOLOGY

Starting from the initial position t = 0 with an initial temperature of 110 K throughout the red colored domain. Here $\boldsymbol{\rho}$ defines the increasing density of water vapour as temperature increases in the next step.

Temperature $\boldsymbol{T_1}$ is applied at the surface of rods, depicted as the red vectors. Regolith particles are colored blue.

The structure starts rotating at ***rpm*** on its z-axis. As a result, vortices create quickly an even distribution of temperature. *Note:* the screenshot is randomly chosen, though for a small time-step.

When the latent heat of water is reached, the ice within the regolith is sublimated and flows towards the open boundary of the system. Vectors are displayed to show the flow towards systems exit.

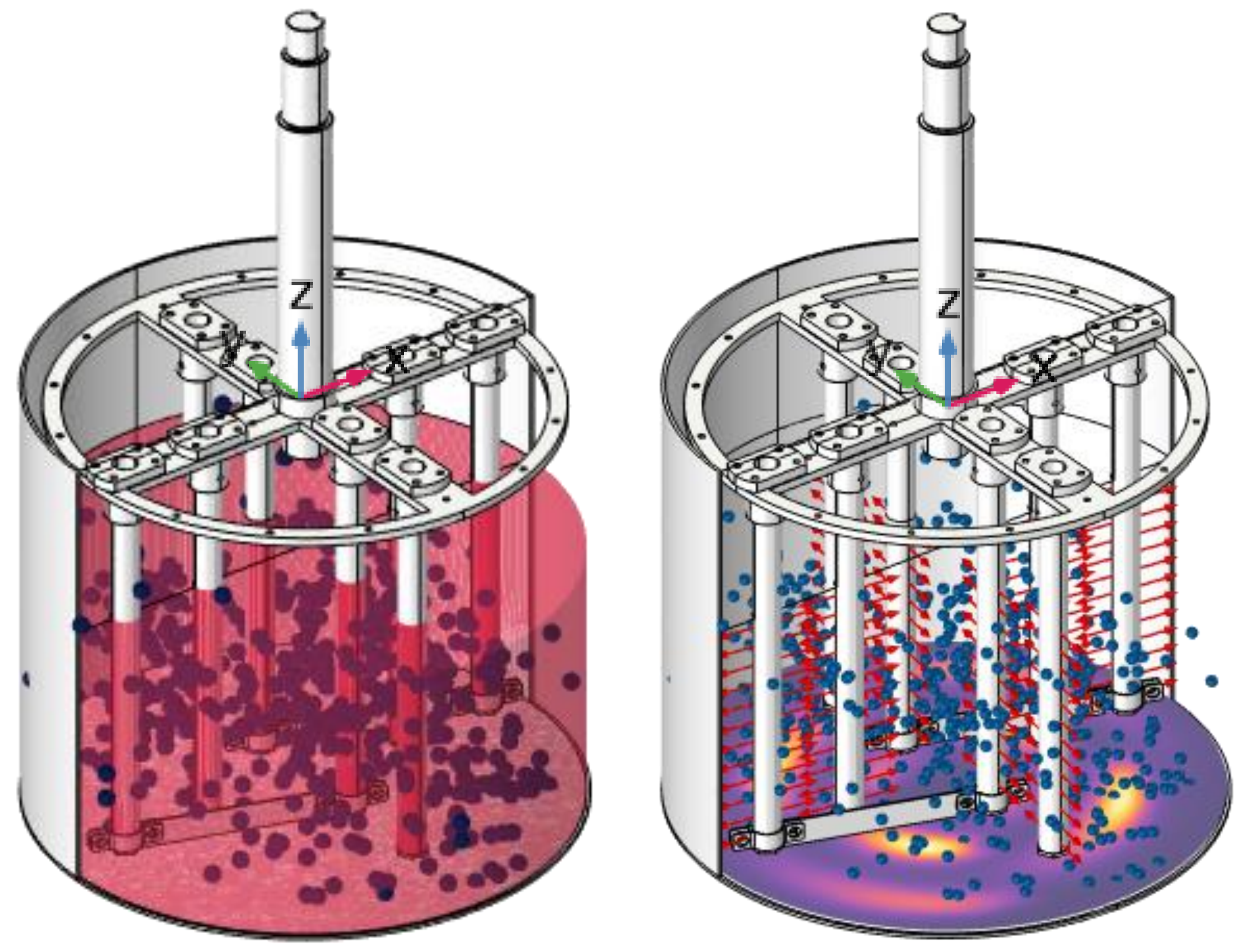

Figure 1/2: Container filled with solid particles of icy-regolith; the rotating rods supply heat for achieving sublimation of ice within the regolith. *Note:* for a clear overview, only a small fraction of the total number of regolith particles are displayed.

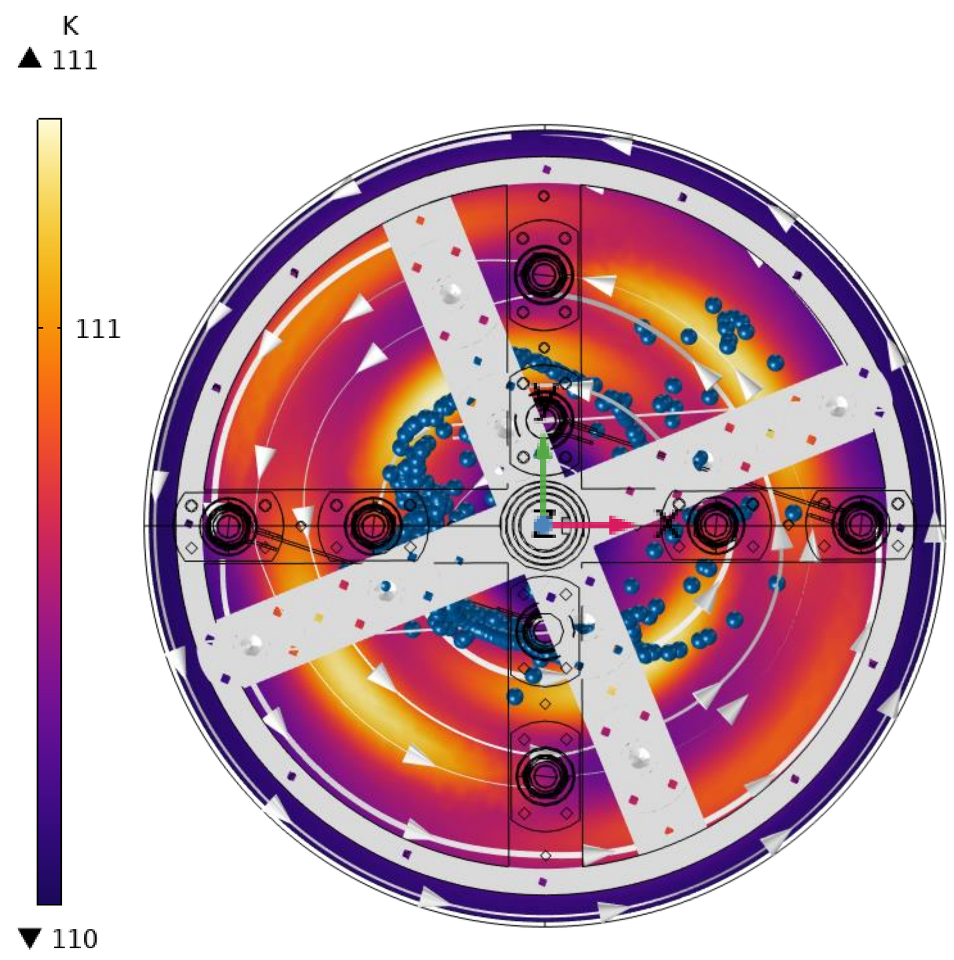

Figure 3: Rotating flow caused by ***rpm*** of the shaft; for increasing the effective thermal conductivity of the mixture.

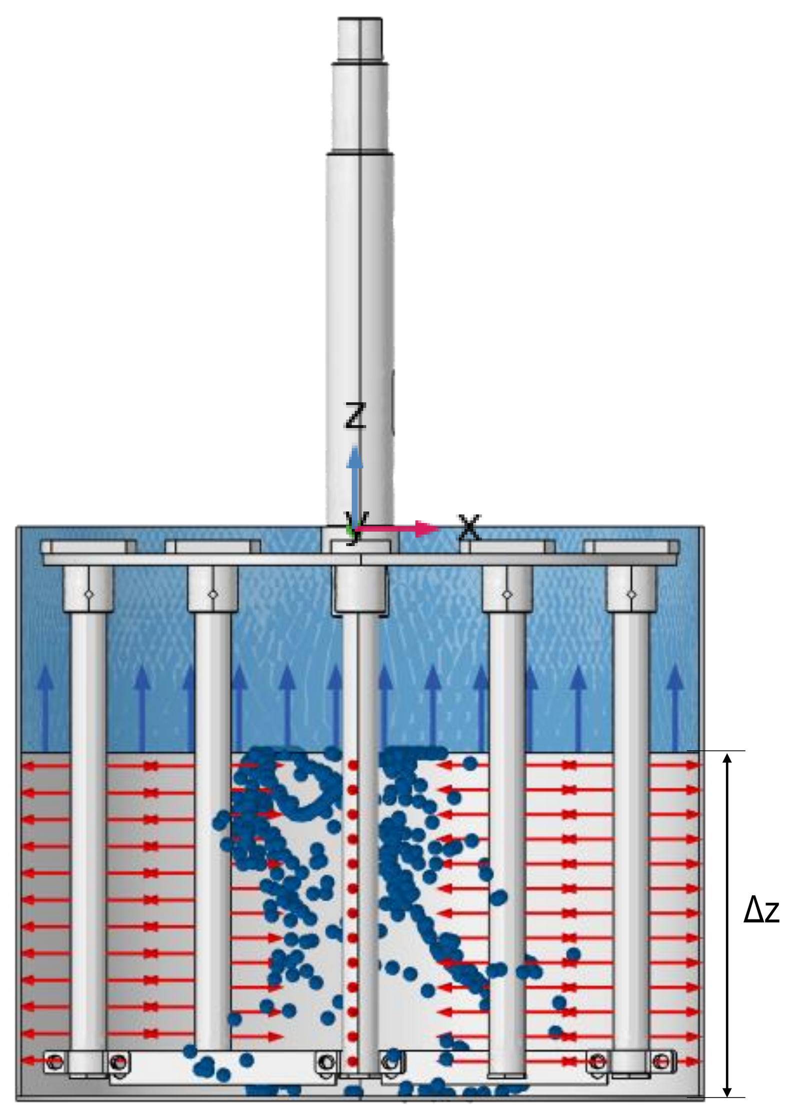

Figure 4: Transport of water vapour; when average temperature reaches T∞ = 273 K, ice is sublimated, and the remaining solid particles only consist of dry Lunar regolith.

ENHANCED THERMAL BEHAVIOUR

The poor thermal properties of Lunar regolith hinder the heat flow of the sample. Ensuring the movement of the Lunar regolith and ice mixture enables even distribution of heat among the regolith particles over a short period. This movement increases particle interactions enhancing the effective thermal conductivity. As a result, the process of heat transfer through the layer of mixture (Δz = 0.15 m) accelerates significantly. At this stage, it is crucial to determine the energy requirements, with particle interactions impacting heat transfer within a rotating bed. The energy required for the system (to overcome the latent heat of water) depends on effective heat transfer, its rotational speed **rpm** and time **t∞** required to reach **T∞** = 273 K. For comparison results are obtained for above configuration and a static assembly for which **rpm** = 0. When a temperature of 273 K is reached the water vapour flows up leaving the system (see fig. 4) causing a decrease in the effective thermal conductivity. Fig 6 shows a major deviation in temperature increase of the Lunar regolith for a rotary configuration; approximately 100 K in timespan of 8 hours.

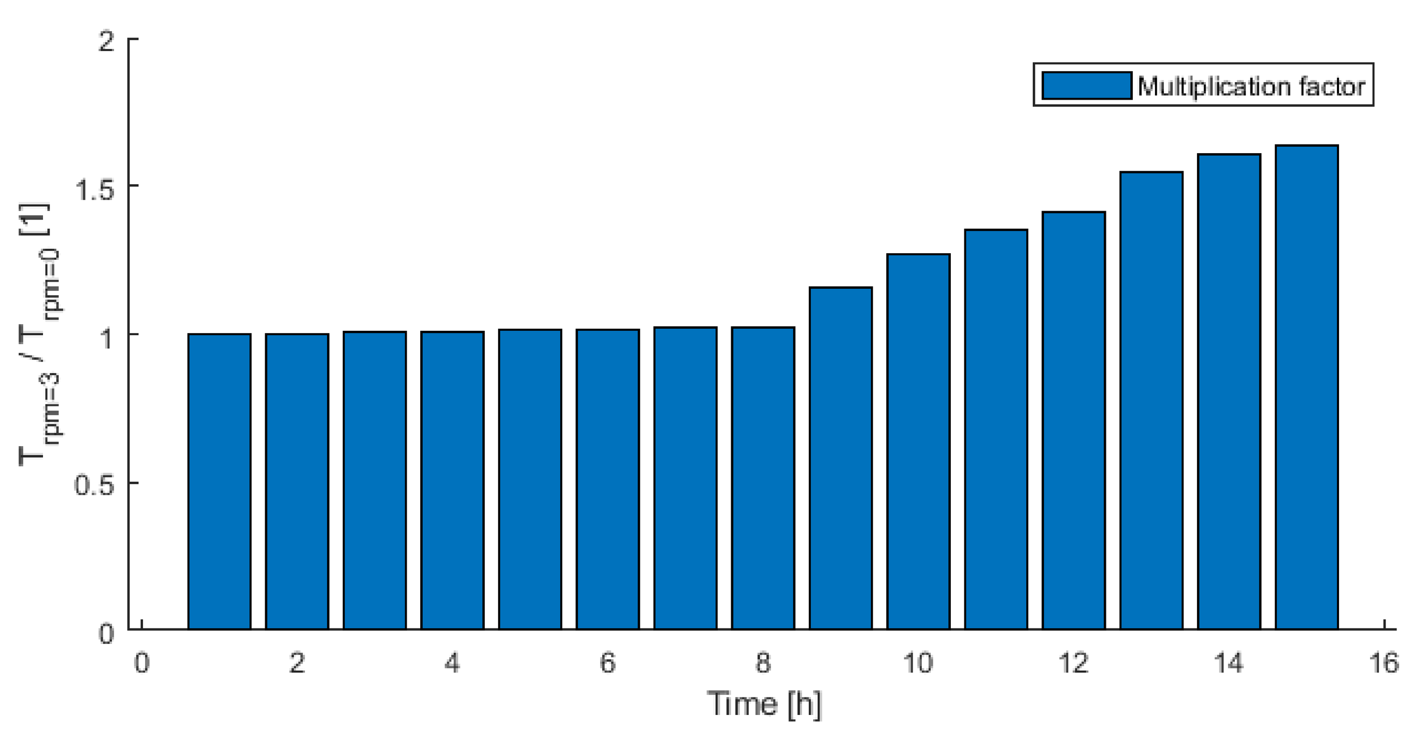

Figure 6: Average temperature of a regolith particle for the rotary and static configuration defined as ratio; after several hours the temperature in the rotary configuration is significantly higher; this design has proven to be more efficient.

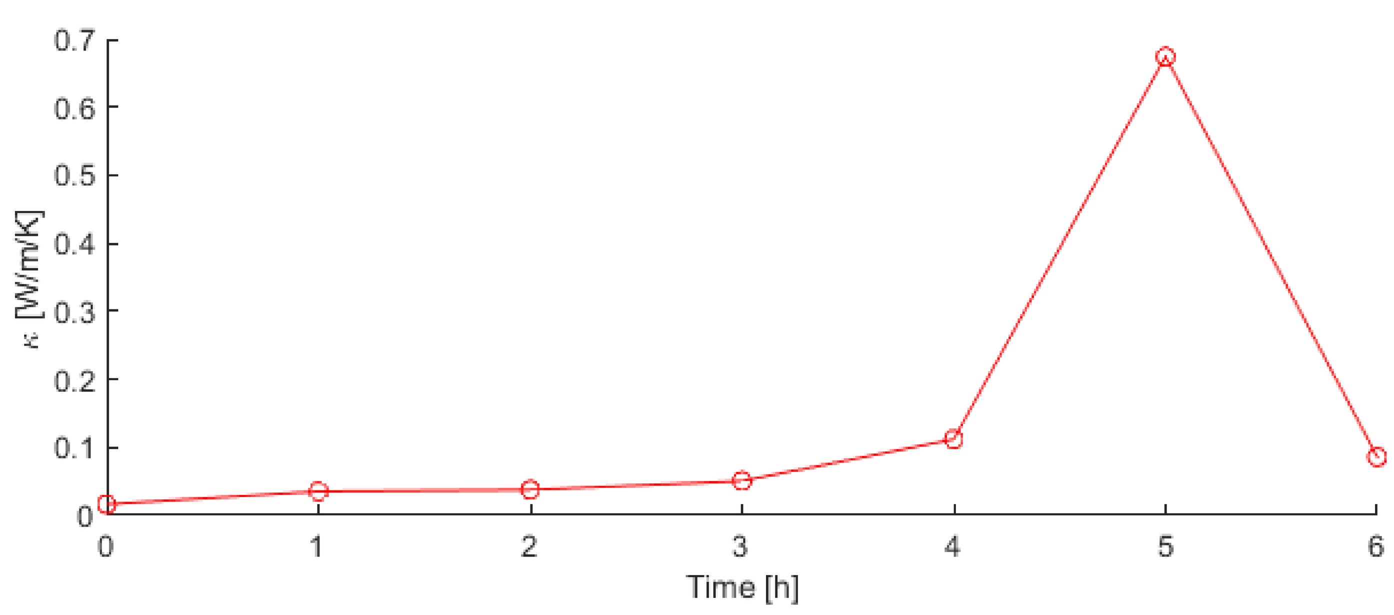

Figure 5: Effective thermal conductivity $\boldsymbol{\kappa}$ as function of time; here $\boldsymbol{\kappa}$ is determined by the calculating the heat fluxes through all directions inside a steady control volume inserted in the mixture; at t = 0 and T_i = 110 K the thermal conductivity is calculated 0.005 W/m/K; $\boldsymbol{\kappa}$ increases significantly at t = 5 h which leads to higher temperature increase in fig. 6

REFERENCES

[1] Kiewiet, L., Hab, N. M., Marchese, F. M. et al. (2022), Trade-off and optimization for thermal Lunar water extraction system.
[2] Heitkamp, M., Development of Lunar Water Extraction Systems: A Comprehensive Approach Integrating CFD and Experimental Validation, 2024 [Unpublished Manuscript], Master's Thesis, German Aerospace Center, DLR
[3] Murphy, D. M., and Koop, T. (2005), ' Review of the vapour pressures of ice and supercooled water for atmospheric applications', Q. J. R. Meteorol. Soc., 131/608: 1539–1565.

This work is part of the DLR internally funded young investigator group "Synergetic Material Utilization" (SMU) established 2021 at the Institute of Space Systems in Bremen, Germany. The group focuses on research and development of ISRU technologies for Moon and Mars exploration.