JASMAC Conference of the Japan Society of Microgravity Application

OR2-6

月のその場資源を用いた溶融凝固プロセスによる有人拠点の建材製法に関する研究

Simulation of melting and solidification process of lunar regolith layer for production of exterior walls

古山史萌 [1]，白鳥英 [2]，永野秀明 [2]，島野健仁郎 [2]
Shiho KOYAMA[1], Suguru SHIRATORI[2], Hideaki NAGANO[2] and Kenjiro SHIMANO[2]
[1] 東京都市大学大学院，Graduate School, Tokyo City University,
[2] 東京都市大学，Tokyo City University,

1. Background and purpose

This study aims to propose efficient manufacturing processes of exterior walls for human residence in lunar surface from local resources: regolith. In recent years, space development has become more active in the world. In Japan, JAXA has a plan of a 500-day long-term lunar exploration in 10 years[1)]. To realize such a long-term manned exploration, it is necessary to construct a residence. Thus, the following three lunar specific environments must be considered: sealing/pressure resistance, radiation resistance, and heat resistance. In addition, for sustainable development, it is preferred to complete the project locally. One possible method that meets these requirements is a sintering using solar power, but it is difficult to satisfy the strength to withstand the internal pressure of 100 kPa that is required to maintain a living space. In order to solve this problem, a melting and re-solidification process can be considered as a sole solution. Since the melting process requires huge amount of energy, preliminary numerical simulations must be executed to design efficient manufacturing processes. To this end, the present study aims to develop a physical model for melting and solidification, permeation, and heat transfer in the lunar regolith layers. In a microgravity environment such as the lunar, the influence of both gravity and surface tension should be considered in the permeation of molten metal into solid regolith layer. In the followings, the order of magnitude of permeation velocities are estimated, and based on these results the physical model is formulated for the melting/solidification process of lunar regolith layers.

2. Estimation of permeation rate

When the molten metal permeates the regolith layer, it is influenced by both gravity and surface tension. The permeation by gravity can be modeled based on the Darcy law as follows[2)]:

$$u_g = \frac{K}{\mu}\rho g_m, \tag{1}$$

where K is the absolute permeability, μ is the viscosity of liquid, ρ is density of the liquid, and g_m is the

acceleration due to lunar gravity. The permeation by surface tension can be modeled based on the Lucas-Washburn rule as follows[3]:

$$u_c = \frac{r\sigma\cos\theta}{4\mu L}, \tag{2}$$

where r is the radius of the porosity, σ is the surface tension of liquid, θ is the contact angle of liquid, μ is the viscosity of liquid, and L is the permeation depth. The concrete values are calculated for Al_2O_3, which is of the most abundant materials of lunar regolith. The physical properties of molten Al_2O_3 were referred from Refs.[4]. The evaluated permeation velocity due to gravity was $u_g = O(10^{-6})$, whereas due to surface tension was $u_c = O(10^{-5}\sim10^{0})$, as shown in the **Fig. 1**. The values of u_c decreases with the depth of penetration.

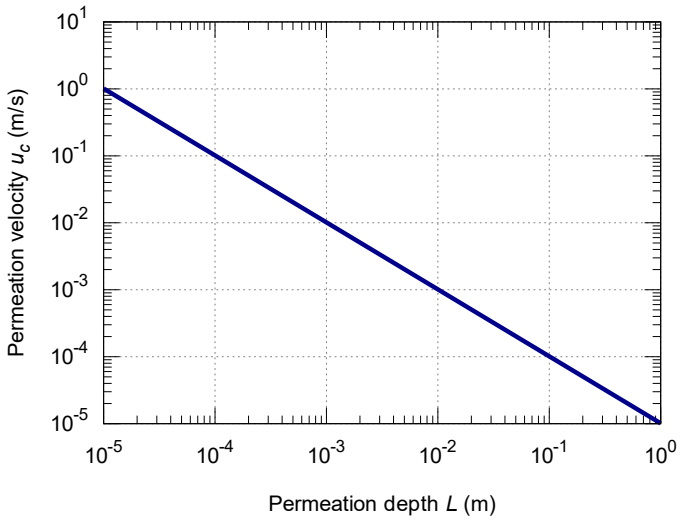

Figure 1. Relationship between permeation depth and velocity due to surface tension.

These results indicate that the permeation of molten metal into regolith in a microgravity environment is dominated by a surface tension. This result is considered in the model formulation described in the following.

3. Formulation of the physical model

3.1. Basic concept of the model

Fig. 2 shows the model considered in the present study. At first, the regolith layer is modeled by porous media. Although about 60% of the regolith has a grain size of 100μm[2], the numerical simulation with the grid size of the same scale with the grain size takes enormous amount of computational cost even for the simple investigation of manufacturing processes. Therefore, we use a coarse-grained model, where the regolith layers are represented by porous media. In this model the location of the gas-liquid interface is not considered. The field variable α for porosity is introduced and the advection of α is solved. In the momentum equation, the pressure loss by the porosity is taken into account. Concerning the melting and solidification, the phase field variable ψ is introduced to represent the phase either the liquid or the solid. The phase change is only considered between liquid/solid phases, and it is described only by temperature field.

The sequence of the simulation is considered as the followings. Initially, the porosity is evenly distributed in the whole domain. Then, the upper boundary is heated which leads melting of the solid phase. Because of the viscosity reduction due to phase change, the porous media is filled by the liquid. After some time, the

upper boundary is cooled, and the liquid phase is solidified. Based on the final porosity distribution, the strength of the layer is evaluated.

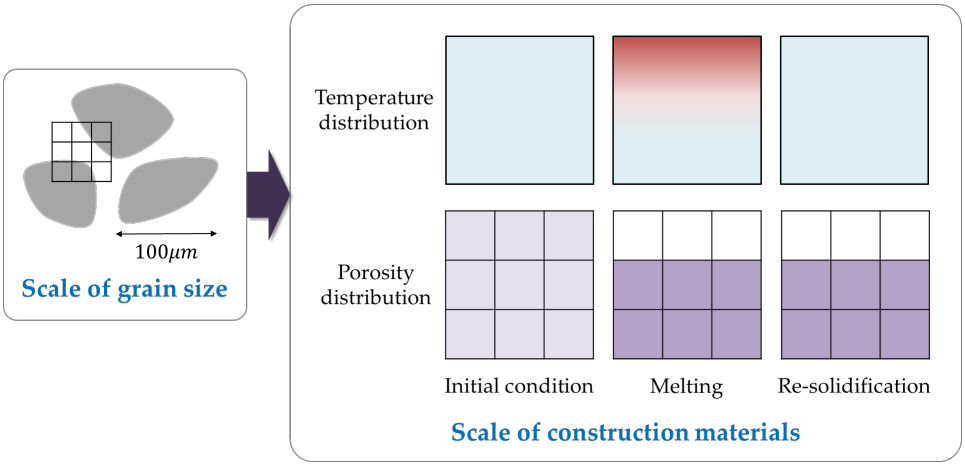

Figure 2. Overview of coarse-grained models.

3.2. Governing equations

Based on the above-mentioned concept the governing equations are formulated as the following conservation laws of mass, momentum, energy.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0, \tag{3}$$

$$\frac{\partial (\rho \boldsymbol{u})}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla p + \nabla \cdot (\mu \nabla \boldsymbol{u}) + \boldsymbol{f}_p + \rho \boldsymbol{g}, \tag{4}$$

$$\frac{\partial (\rho c_p T)}{\partial t} + \nabla \cdot (\rho c_p T \boldsymbol{u}) = \nabla \cdot (\lambda \nabla T) + \Delta h \rho_l \frac{\partial \psi}{\partial t}, \tag{5}$$

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \boldsymbol{u}) = 0, \tag{6}$$

where ρ, μ, c_p, λ are density, viscosity, specific heat, and thermal conductivity of the mixture, respectively. $\boldsymbol{u}, p, T$ are the velocity, pressure, and temperature, respectively. The field variables α stands for the volume fraction of the phase which is not gas. $\alpha = 1$ is corresponding to the control volume is filled with liquid or solid. The field variable ψ stands for the fraction of the liquid phase. If we denote the individual volume fractions ϕ_g, ϕ_l, and ϕ_s for gas, liquid, and solid respectively, the relation between fractions is written by

$$\phi_g + \phi_l + \phi_s = 1, \tag{7}$$

$$\begin{aligned} \phi_g &= (1 - \alpha), \\ \phi_l &= \alpha \psi, \\ \phi_s &= \alpha (1 - \psi). \end{aligned} \tag{8}$$

Physical properties for the mixture are formulated by the weighted average of the three phases. The arbitrary physical property X is evaluated as:

$$X = \phi_s X_s + \phi_l X_l + \phi_g X_g = \alpha (1 - \psi) X_s + \alpha \psi X_l + (1 - \alpha) X_g. \tag{9}$$

The phase change between liquid and solid are determined only by the temperature as:

$$\phi(T) = \begin{cases} 0, & \tilde{T} < -\delta_T/2, \\ \frac{1}{2} + \frac{\tilde{T}}{2\delta_T} + \frac{1}{2\pi}\sin\left(\frac{\pi\tilde{T}}{\delta_T}\right) & |\tilde{T}| \leq \delta_T/2, \\ 1, & \tilde{T} > \delta_T/2, \end{cases} \tag{10}$$

where $\tilde{T} - T_m$ is the temperature difference from the melting point T_m. The term $\boldsymbol{f}_p$ in the Navier-Stokes equation denotes the pressure loss by the porous media, which is formulated by the Kozeny-Carman model:

$$\begin{aligned} \boldsymbol{f}_p &= -A(\alpha)\boldsymbol{u}, \\ A(\alpha) &= C\frac{\mu}{D^2}\frac{(1-\alpha)^2}{\alpha^3 + \epsilon}, \end{aligned} \tag{11}$$

where C is the coefficient determined by the shape of the regolith grain, D is the diameter of the grain, and ϵ is the small value which is introduced to avoid singularity. These governing equations are implemented on the open-source CFD toolbox OpenFOAM-v2112 as a customized solver.

The validity of the developed solver and the representative results will be shown in the conference.

References

1) Space Exploration Systems Engineering Unit, International Space Exploration Center, JAXA: Japan's Scenario for International Space Exploration, JAXA proposal 2021 (Public Version) (2022) (in Japanese).
2) Grant H. Heiken, David T. Vaniman, and Bevan M. French: Physical properties of the lunar surface, Lunar sourcebook a user's guide to the moon, Chapter 9, *Cambridge University Press* (1991).
3) David Benavente, Peter Lock, M Angeles Garcia Delcura, and Salvador Ordonez: Predicting the Capillary Imbibition of Porous Rocks from Microstructure, *Transport in Porous Media*, **49**, 59-76 (2002).
4) Takehiko Ishikawa, Chihiro Koyama, Hirohisa Oda, Hideki Saruwatari, and Paul-Francois Paradis: Status of the Electrostatic Levitation Furnace in the ISS-Surface Tension and Viscosity Measurements, *Int. J. Microgravity Sci. Appl.*, 39 (2022) 390101.

© 2022 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/li censes/by/4.0/).