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OR1-2

月面での砂礫溶融凝固プロセスの物理モデル構築

physical modeling of legolith partiacle melting soildification methods in lunar surface

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1. Introduction

1.1. Background

For long-term manned lunar exploration, which is planned in the near future, lunar human bases need to be constructed. Several designs for lunar habitats have been proposed. One of these is shown in Ref.1). In this proposal, the lunar base has outer walls made from in-situ lunar regolith. However, to bind the regolith, binding agents must be transported from Earth. There are two methods to bind the lunar regolith without external materials. These methods are the sintering method and the melting-solidification method. Obayashi and JAXA conducted experiments on binding a lunar regolith simulant using only itself. The structures made by the sintering method and the melting-solidification method with the lunar regolith simulant are shown in Ref.2). The results indicate that the structure made by the sintering method has countless pores, whereas the structure made by the melting-solidification method is sufficiently filled and has almost no pores. Therefore, the melting-solidification method is a more appropriate way of manufacturing materials for a manned base. For manufacturing construction materials for the lunar base using the regolith, preliminary simulations are necessary. From this standpoint, this study aims to establish a physical model that can simulate the regolith melting and solidification process.

1.2. Direction of this study

Figure 1 shows the situation assumed in this study. The regolith is randomly placed at first. Then, it is heated from above. This process results in the regolith being fully melted and finally solidified. We establish a physical model that can simulate regolith melting-solidification methods, but if we simulate at the scale of the regolith particle size, as shown in **Fig. 1**, the numerical cost would be enormous. Therefore, in this study, by averaging the amount of each phase as a percentage of the volume in each numerical cell like **Fig. 2**, we develop a coarse-grained physical model. The governing equations are formulated in the following sections.

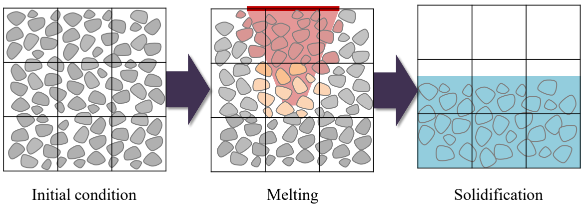


Figure 1. The situation assumed in this study.

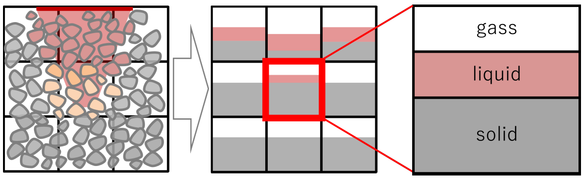
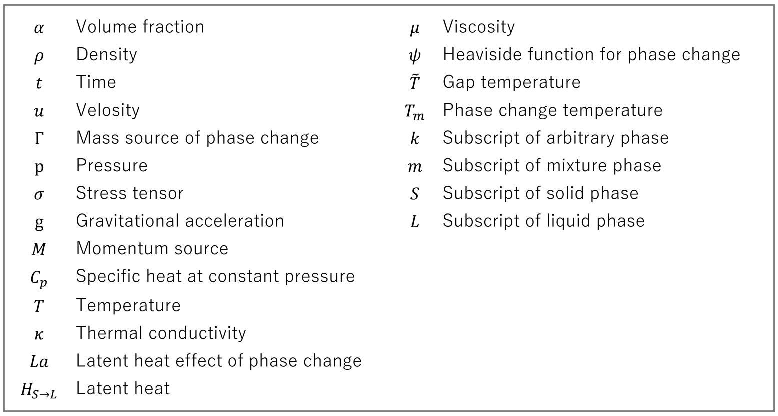


Figure 2. The schematic of coarse grained approach.

2. Physical Modeling and Governing Equations

We propose a coarse-grained physical model that can account for the phase change and transport properties of regolith. The physical model is composed of conservation equations for each phase and constitutive equations. In particular, stress models and a phase change model are applied as constitutive equations. In this study, the phase change is dependent only on the temperature, which is determined by the mixture temperature field.



α	Volume fraction	μ	Viscosity
ρ	Density	ψ	Heaviside function for phase change
t	Time	$\tilde{T}$	Gap temperature
u	Velocity	T_m	Phase change temperature
Γ	Mass source of phase change	k	Subscript of arbitrary phase
p	Pressure	m	Subscript of mixture phase
σ	Stress tensor	S	Subscript of solid phase
g	Gravitational acceleration	L	Subscript of liquid phase
M	Momentum source		
C_p	Specific heat at constant pressure		
T	Temperature		
κ	Thermal conductivity		
La	Latent heat effect of phase change		
$H_{S\to L}$	Latent heat		

Figure 3. Nomencleature in this study.

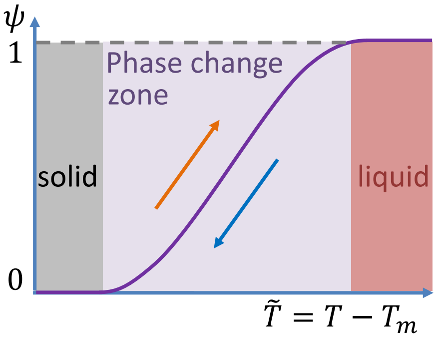


Figure 4. Heaviside function used in phase change.

When a phase change occurs, the balances of mass, momentum, and energy are changed. To ensure consistency, the effect of phase change is considered in the conservation equations as phase change terms. Note that the constants and variables used in this study are listed in **Fig. 3**.

2.1. Conservation laws

The conservation laws are the primary equations of this model. The mass, momentum and energy equations are written in the following form.

$$\frac{\partial \alpha_k \rho_k}{\partial t} + \nabla \cdot (\alpha_k \rho_k \boldsymbol{u}_k) = \Gamma_k, \tag{1}$$

$$\frac{\partial \alpha_k \rho_k \boldsymbol{u}_k}{\partial t} + \nabla \cdot (\alpha_k \rho_k \boldsymbol{u}_k \boldsymbol{u}_k) = -\alpha_k \nabla p + \nabla \cdot \alpha_k \boldsymbol{\sigma}_k + \alpha_k \rho_k \boldsymbol{g} + \boldsymbol{M}_k, \tag{2}$$

$$\frac{\partial \rho_m C_{p,m} T}{\partial t} + \nabla \cdot (\rho_m C_{p,m} T \boldsymbol{u}_m) = \nabla \cdot (\kappa_m \nabla T) + La. \tag{3}$$

Equations (1) and (2) describe the mass and momentum balances for each phase. On the other hand, in this study, we assume that each phase has the same temperature. Therefore, the energy equation Eq. (3) is defined for the mixture field. where, the volume fraction of each phase must satisfy constraint of the volume conservation rule as follows.

$$\sum_k \alpha_k = 1. \tag{4}$$

2.2. Constitutive laws

To close the system of the physical model, some constitutive laws are necessary. Equations (1) to (3) mainly require of stress models and a phase change model.

2.2.1. Summation rules

The summation rules are defined as constraints to relate the properties of each phase to those of the mixture phase. The physical properties, such as density and specific heat, used in the energy equation Eq. (3) are defined as

$$\sum_k \alpha_k \rho_k = \rho_m \tag{5}$$

$$\sum_k \alpha_k \kappa_k = \kappa_m, \tag{6}$$

$$\sum_k \frac{\alpha_k \rho_k \boldsymbol{u}_k}{\rho_m} = \boldsymbol{u}_m \tag{7}$$

$$\sum_k \alpha_k C_{p,k} = C_{p,m}. \tag{8}$$

2.2.2. Stress model

In this study, regolith is treated as both the liquid phase and the solid phase. By applying appropriate stress models, the physical model can treat regolith as both the liquid and the solid. Fluid stress is a viscous stress governed by Newton's law of viscosity as

$$\sigma_k = \mu_k[\nabla \boldsymbol{u}_k + (\nabla \boldsymbol{u}_k)^T]. \tag{9}$$

This stress is applied to the molten regolith and the void phase which is treated as air in this study. Although the solid phase is considered as fluid in this paper because we only partially evaluate the physical model, we will implement the solid phase stress model in future work.

2.2.3. Phase change model

In this study, phase change depends only on temperature. When the temperature of the system exceeds the phase change temperature, the solid phase is changed into the liquid phase according to a Heaviside function as shown in **Fig. 4**. If the temperature rises and reaches the phase change zone, the volume fraction of the liquid phase increases (indicated by the orange arrow). In contrast, if the temperature decreases and reaches the phase change zone, the volume fraction of the liquid phase decreases (indicated by the blue arrow). To express this behavior, we introduce the variable

$$\psi(T) = \frac{\alpha_L}{\alpha_S + \alpha_L}, \tag{10}$$

which is the ratio of the liquid volume fraction to the sum of the liquid phase and the solid phase volume fractions, which is determined by the Heaviside function. This function ψ is used to evaluate the phase change as

$$\Gamma_L = \rho_L \frac{d\alpha_L}{dt} = \rho_L(\alpha_L + \alpha_S)\frac{d\psi(\tilde{T})}{dt} \tag{11}$$

$$\Gamma_S = -\Gamma_L, \tag{12}$$

where, the Heaviside function ψ is defined as a function of the gap temperature Eq. (13) so that the center point of the phase change zone shown in **Fig. 4** corresponds to the phase change temperature T_m.

$$\tilde{T} = T - T_m \tag{13}$$

and then,

$$\boldsymbol{M}_L = \begin{cases} \Gamma_L \boldsymbol{u}_S & (\Gamma_L \geq 0) \\ \Gamma_L \boldsymbol{u}_L & (\Gamma_L < 0) \end{cases}, \quad \boldsymbol{M}_S = \begin{cases} \Gamma_S \boldsymbol{u}_L & (\Gamma_S \geq 0) \\ \Gamma_S \boldsymbol{u}_S & (\Gamma_S < 0) \end{cases} \tag{14}$$

$$La = -\Gamma_L H_{S\rightarrow L} \tag{15}$$

The terms Eq. (14) and Eq. (15) represent the influence of phase change on the momentum equation Eq. (2) and the energy equation Eq. (3), respectively. In particular, Eq. (15) is represents the effect of latent heat.

3. Numerical results

We verified the fundamental functions of the physical model, phase change and phase transport. The results of the verifications are shown in **Fig. 5** and **Fig. 6**, respectively. In **Fig. 5**, temperature, the liquid phase volume fraction and the solid phase volume fraction are arranged and indicated from left to right in each section. These are divided into a melting verification (a) and a solidification verification (b). The passage of time is also indicated. In the melting verification, the system is heated from above, whereas in the solidification verification, the system is cooled from above. In these verifications, the solid phase is treated as a fluid phase for simplicity. The results show the ability to consider the phase change of both melting and solidification. In **Fig. 6**, we considered a situation in which a water droplet is transported with an air flow in a tube. The droplet has an initial velocity and it is transported by its velocity. In **Fig. 6**, the gravitational acceleration is neglected to avoid collision with the lower wall. The result shows the physical model has the ability to consider phase transport.

Acknowledgments

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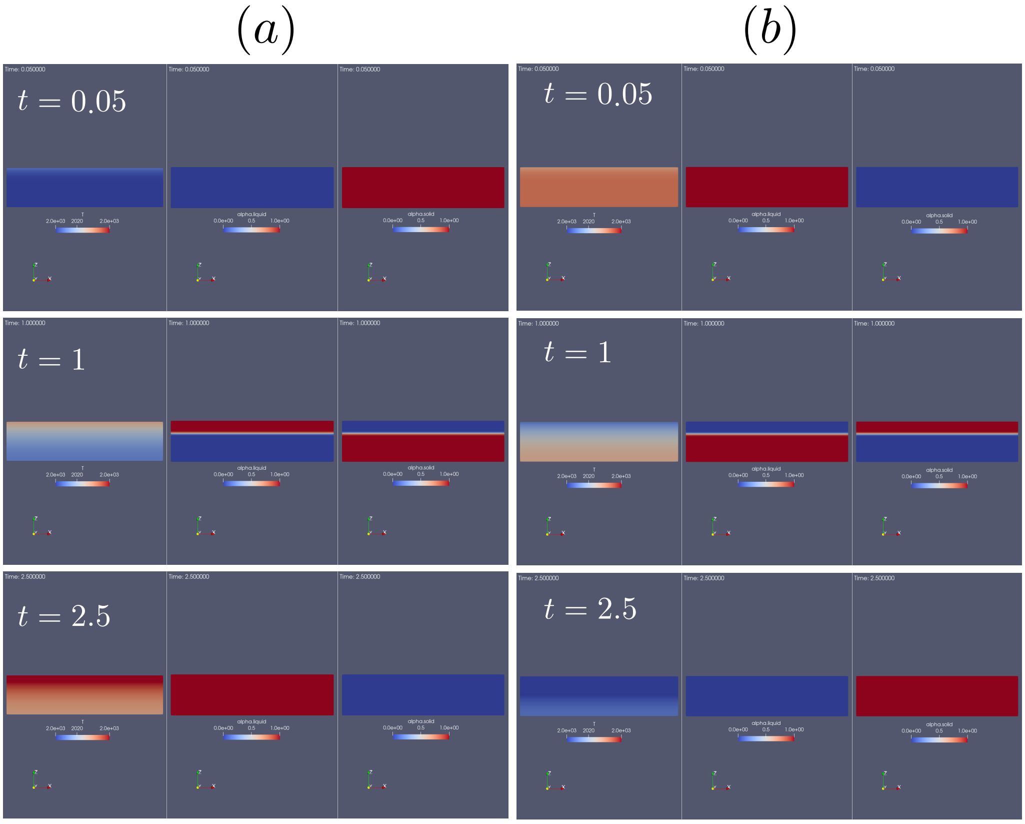

Figure 5. The result of phase change verification. (a)heating from above, (b)cooling from above.

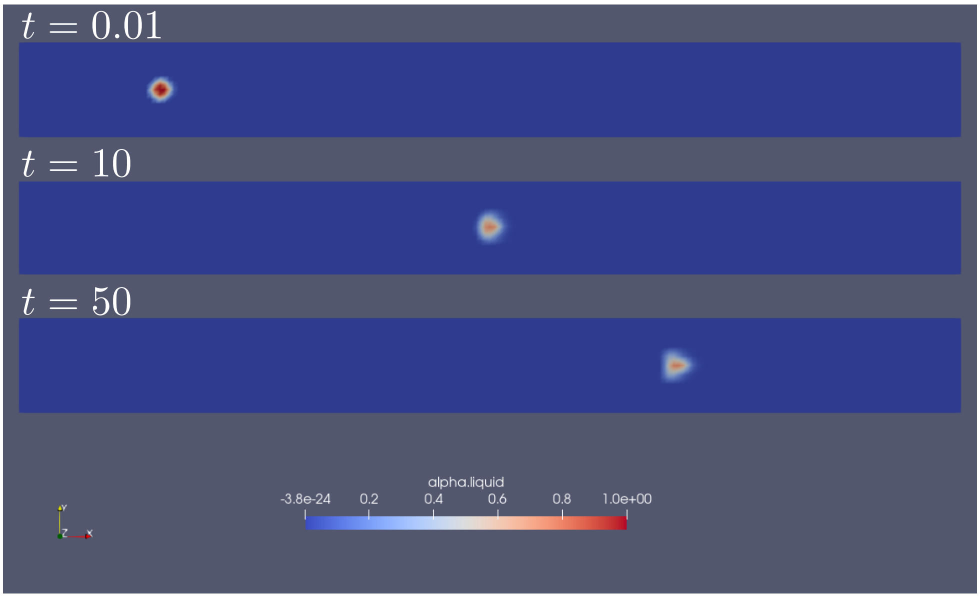

Figure 6. The result of droplet transport varification.

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