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非定常計算を考慮した砂礫内伝熱モデルの構築

Modeling of Heat Transfer for Particle Materials Capable of Transient Calculation

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1. Introduction

Global space development initiatives are increasingly focused on long-term lunar exploration. Establishing sustainable moonbases is essential for these endeavors. To achieve sustainability on the Moon, In-Situ Resource Utilization (ISRU), using local resources like lunar regolith, is preferable to transporting materials from Earth, especially given the high transportation costs. The Melting and Solidification Processes (MSP), a key ISRU technique, presents a promising approach for lunar construction 1). Given the strict lunar environment, numerical simulation is indispensable for thorough material design. Although numerical simulation is essential for designing materials for MSP, widely established models for this specific application are lacking. The heating behavior of particle materials, influenced by contact interactions in a lunar environment, differs significantly from that of continuum materials. Traditional methods like the Finite Volume Method (FVM) are computationally impractical for particle systems due to the high calculation cost of meshing. To address computational costs, previous studies 2), 3) have proposed heat transfer network models for particle materials. However, these models have significant limitations for MSP simulation. Their applications are often limited to steady-state, Dirichlet boundary problems and exhibit unignorable errors in heat transfer calculations during initial transient phases. While introducing a correction coefficient may suppress these errors, the lack of a reliable method for determining this parameter makes the model impractical. Therefore, the purpose of this study is to establish a transient heat transfer network model for particle materials. Our model is designed to be as accurate as FVM while maintaining a low computational cost. In addition, we propose a reliable and systematic method for determining the correction coefficient, thereby eliminating the need for a trial-and-error approach. This enhances the practicality of network models for simulating the full MSP.

2. Model Formulation

Our heat transfer network model focuses solely on heat conduction, neglecting the effects of heat convection and radiation. We modeled the particles as two-dimensional circles with varying sizes, but all share uniform physical properties, such as thermal diffusivity. To simulate transient heat transfer between particles, we do not impose continuous heating from the simulation environment. Instead, we apply an initial temperature to a selected single particle within the system and evaluate the heat transfer to its contacting neighbors. Our proposed model is based on the heat conduction equation as follows:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \tag{1}$$

where T, t and α denote temperature, time and thermal diffusivity. We then applied FVM's discretization method 4) for formulation as follows:

$$T_i^{n+1} - A_{ij} \sum_{j \neq i} \left(T_j^{n+1} - T_i^{n+1} \right) \beta = T_i^n \tag{2}$$

where n, A_{ij}, $(\cdot)_k$ and β denote time step, coefficient dependent on mesh, particle ID and the correction parameter, respectively. Our approach involves an approximation for calculating heat flux, which is necessary for efficient computation. Initially, this approximation led to errors in heat flux calculations. To solve this, we

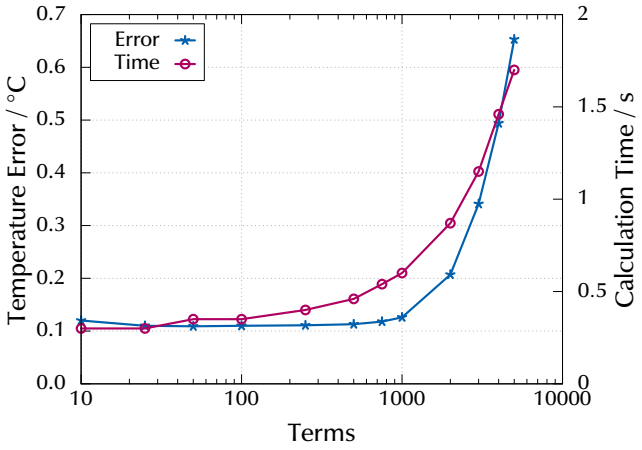

Figure 1. Temperature error as a function of the number of terms.

introduced a correction parameter, β, which is systematically determined to ensure accuracy. The value of β is derived from the analytical solution. We model the heat transfer between the centers of two contacted particles as a one-dimensional heat conduction problem with these conditions below: Boundary Conditions: Dirichlet boundary of non-dimensionalized temperatures of 1 and 0 at the left and right sides, respectively. Initial Conditions: Non-dimensionalized temperature of 1 in $0 \leqslant X \leqslant 0.5$, and 0 in $0.5 < X \leqslant 1$. The solution expressed as:

$$T^*(X, t^*) = (1 - X) - \sum_{m=1}^{\infty} \frac{(-1)^m}{m\pi} \sin(2m\pi X) \exp\left(-4m^2\pi^2\alpha t^*\right) \tag{3}$$

where T^*, t^* and X denote non-dimensionalized temperature, non-dimensionalized time and non-dimensionalized distance between the centers of contacting particles. The analytical solution allows us to calculate the temperature gradient at the point of $X = 0.5$ as:

$$\left.\frac{\partial T^*(X, t^*)}{\partial X}\right|_{X=0.5} = -1 - 2\sum_{m=1}^{\infty} \exp\left(-4m^2\pi^2\alpha t^*\right) \tag{4}$$

We then use this derived temperature gradient to systematically calculate β in our model, ensuring a non-empirical approach. Finally, we performed a validation study by simulating the same case with FVM. To compare the results, we evaluated and compared the mean temperature of each particle from both our model and the FVM simulation. This demonstrates the practicality and accuracy of our proposed network model.

3. Calculation Results

We implemented our formulation using Python to evaluate the model's performance. For validation purposes, the thermal diffusivity was set to 10^{-6} m^2/s.

3.1. Conservation of Energy

In a closed system without external heating, we evaluated the error between the theoretical equilibrium temperature and the final results from both our model and FVM. Our model exhibits an error of -5×10^{-7}°C, in contrast to FVM's error of -2×10^{-4}°C. This result suggests that our model accurately satisfies the law of conservation of energy.

3.2. Evaluation of Terms vs. Accuracy and Calculation Time

While the analytical solution for the correction parameter β is an infinite number of terms, we must limit these for practical numerical calculations. Therefore, we evaluated the impact of limiting the number of terms on both computational accuracy and calculation time. As shown in **Fig. 1**, we found that an increase in the number of terms leads to a corresponding increase in the calculation time. However, the temperature accuracy has not necessarily improved. Based on these results, we found that using the first 50 terms provides an optimal balance, allowing for accurate results while maintaining a low computational cost.

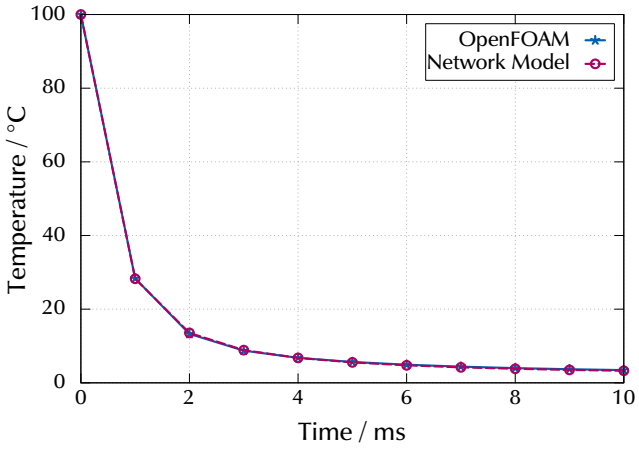

Figure 2. Temperature evolution histories of two particles.

3.3. Validation of Temporal Change of Temperature

We validated the temperature fluctuation of each particle under the same conditions. The initial transient phase of the simulation shows sharp temperature fluctuations, which can lead to significant errors. We focused our validation on this phase and found that our model's mean temperature error was approximately 0.11°C. **Fig. 2** shows a comparison of the temperature fluctuation history for a particle with an initial temperature. As demonstrated, our model successfully produces results with the same accuracy as FVM, validating its practicality for solving these types of problems.

Acknowledgments

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