EFFECT OF MICROCRACKS ON THE THERMOPHYSICAL PROPERTIES OF RYUGU.

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Introduction: The Hayabusa2 mission [1] investigated the near-Earth asteroid (162173) Ryugu by remote sensing and in-situ measurements from June 2018 to November 2019 and returned samples to Earth in December 2020. We refer to [2] for a comprehensive review of the mission findings and a comparison of results obtained during the remote sensing, in-situ and sample analysis phases.

Thermal inertia measurements performed remotely from the TIR thermal imager onboard the orbiter [3], and the in-situ measurements by the MARA radiometer [4] on the MASCOT lander agree well with each other. They report thermal inertias of (225±45) $\mathrm{Jm^{-2}K^{-1}s^{-1/2}}$ and (256±34) $\mathrm{Jm^{-2}K^{-1}s^{-1/2}}$, respectively. However, the analysis performed on the returned samples [5] resulted in an inertia value of (890±45) $\mathrm{Jm^{-2}K^{-1}s^{-1/2}}$, thus about three times as large as the inertia determined in-situ. This discrepancy between properties on micro (sample) to global length scales allures to a missing link in our understanding of thermal conductivity of carbonaceous chondrites.

While the reason behind the discrepancy remains unknown, it has been proposed that the difference in thermophysical properties between the micro- and macro-scales could be caused by a thermal shielding effect on intermediate length scales [6]. The day-night cycle on the asteroid and the associated temperature excursions could induce a state of thermal stress in the material, thus resulting in fatigue and the development and growth of cracks [7]. Cracks would extend to a few skin depths $d_\epsilon = \sqrt{\kappa P/\pi}$ into the bulk material, where $\kappa = k/\rho c_p$ is the thermal diffusivity, ρ is the bulk density, c_p is specific heat, and P is the period of forcing (day-night cycle). Remote sensing instruments like MARA and TIR would be sensitive to a region extending to similar depths, while the returned samples could contain considerably less cracks, as is indicated in Figure 1.

Modeling: We plan to test the influence of cracks on the thermophysical properties of Ryugu using numerical simulations of heat transfer in a particle bed, where individual particles are connected through sintering bonds at the particle necks. In this way, we can simulate competent aggregates and we use the LIGGGHTS(R)-PUBLIC program package to implement the discrete element method on the bed of particles. LIGGGHTS is an open source software built for simulating general granular motion and atomic/molecular dynamics. The inter-particle forces are governed by a (user-selected) contact model which can encompass interactions via elastic forces, rolling friction, cohesion and the surface geometry of particles. We use the package to generate a close packing of the particle bed and to prescribe the inter-particle contact areas.

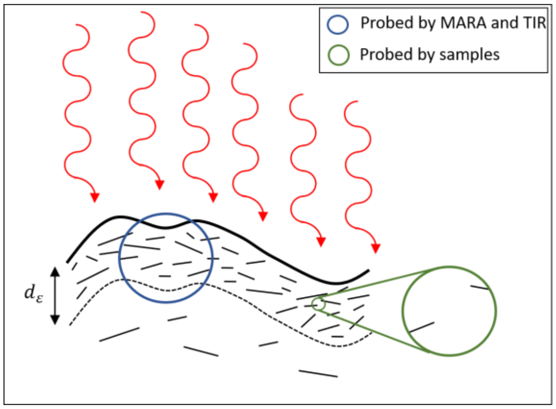

Fig.1: Conceptual model of scale dependency of thermophysical properties. The range of materials sampled by in-situ and remote sensing instruments MARA and TIR is indicated in blue, while the returned samples are indicated in green. On large scales, the material may exhibit abundant cracks due to insolation induced fatigue, while samples may contain only a few cracks.

In addition to mechanical interactions, the package also provides means to study the thermal energy transport between particles in contact. This is governed by the thermal conductivities of the particles and their contact areas, which we parameterize to take the effect of interparticle bonds into account. Heat flow $\dot{Q}_{i-j}$ between particles i and j is then given by

$$\dot{Q}_{i-j} = h_{c,i-j} \Delta T_{i-j} \tag{1}$$

where $h_{c,i-j}$ is the coefficient of heat transport and ΔT_{i-j} the temperature gradient between the particles. In the absence of heat sources, temperature of the particle T_i as a function of time t is then calculated starting from the initial (isothermal) state according to

$$m_p c_p \frac{dT_i}{dt} = \sum_{contacts} \dot{Q}_{i-j} \qquad (2)$$

where m_p is particle mass.

To determine thermal conductivity of the particle bed, we impose temperature boundary conditions T_L and T_R on the left- and right-hand side of the computational domain, while other boundaries are treated as adiabatic. Simulations are run until a quasi steady-state is reached and the total heat flow Q_t across the assembly is then calculated. Bulk thermal conductivity k_{bulk} of the assembly is then calculated from Fourier's law according to

$$k_{bulk} = \frac{Q_t \cdot \Delta x}{T_R - T_L} \qquad (3)$$

where Δx is the distance between the plates.

Results: Figure 2 shows the results of a simulation calculating heat transport across a bed of monodisperse particles. Individual particles are assumed to have a thermal conductivity of 1 W m^{-1} K^{-1}. Prescribing the particle contact radius r_c to be 1.5% of the particle radius R_p, the resulting bulk thermal conductivity of the assembly was determined to be 0.0215 W m^{-1} K^{-1}. This result can be compared to analytical models for smooth particles of thermal conductivity k_m = 1 W m^{-1} K^{-1}, for which the bulk thermal conductivity is given by [8]

$$k_{bulk} = \frac{4}{\pi^2} k_m (1 - \varphi) C \frac{r_c}{R_p} \qquad (4)$$

Here, φ and C are the bulk porosity and particle coordination number , respectively.

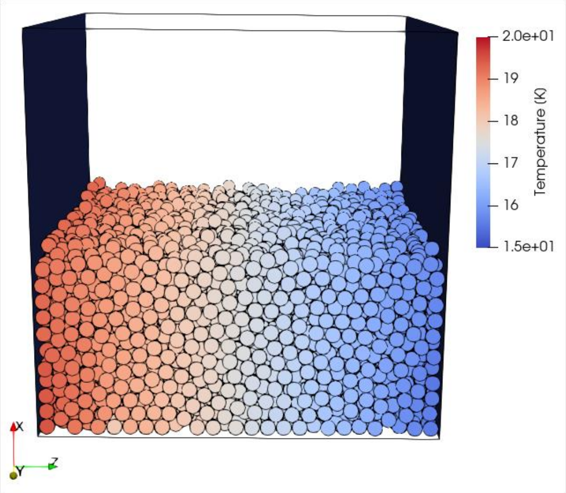

Fig. 2: First results of simulating heat flow through a bed of monodisperse particles between two plates. Color indicates particle temperature going from red (hot) to blue (cold).

Using Eq. (4) and the porosity and coordination number as determined from the particle assembly in Fig. (2), the resulting thermal conductivity was found to be 0.0187 W m^{-1} K^{-1} and thus in reasonable agreement with the fully numerical result obtained using the method described above.

Summary and Outlook: We will study the influence of cracks on the bulk thermal conductivity of particle assemblages by first setting up a homogeneous closely packed particle bed in contact with the hot and cold walls. Then, bulk thermal conductivity of the bed will be calculated according to the above procedure. Cracks will then be introduced into the model by removing particles to form void spaces as illustrated in Figure 3. Models will then be rerun from the initial state including the cracks to obtain the bulk thermal conductivity of the disrupted assembly.

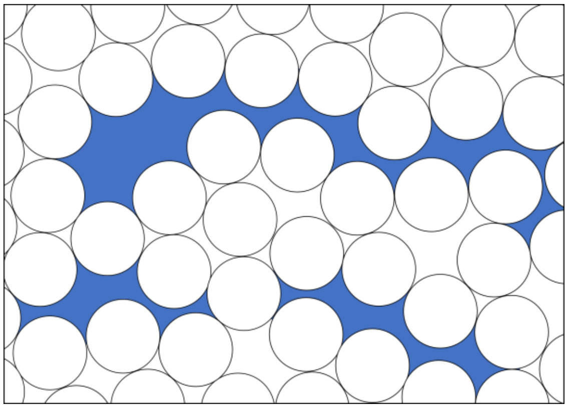

Fig. 3: Modelling approach including cracks induced by thermal fatigue using the discrete elements method. Fatigue induced cracks separating the particles are indicated here in blue.

In this way, we will systematically study the influence of crack size and shape as well as the influence of the amount of cracks on thermal conductivity. Thus, we will be able to quantify the form and amount of material disruption needed to explain the observed reduction of bulk thermal conductivity between the micro- and macro-scales.

References: [1] S. Watanabe et al. *Space Science Reviews* 208, 1 (2017), p. 3–16. [2] K. Otto et al. *Earth, Planets and Space* 75, 1 (2023), p. 51. [3] T. Okada et al. *Nature* 579 (2020), p. 518–522. [4] M. Hamm et al. *Nature Communications* 13, 364 (2022). [5] S. Tanaka et al. *53rd Lunar and Planetary Science Conference* LPI Contribution No. 2678. [6] T. Nakamura et al. *Science* 379, 6634 (2023) eabn8671. [7] M. Delbo et al. *Nature* 508 (2014), p. 233. [8] N. Sakatani et al. *AIP Advances* 7, 015310 (2017).