NUMERICAL HEAT TRANSFER ON HIGHLY POROUS AGGREGATES AND ASTEROID BOULDERS.

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Introduction. Based on its recent success, the Hayabusa2 mission (2014-2020) [1] has returned samples of C-type asteroid Ryugu (162173) to Earth, and the sample analysis is currently ongoing [2]. Remote sensing [3] and in-situ [4] data indicate an unexpectedly low thermal inertia for the majority of rocks on Ryugu [5], which has generally been attributed to a high intrinsic porosity. However, results obtained from returned samples indicate much lower porosities. The origin of this discrepancy is currently unknown and different causes, including a potential scale dependence of thermophysical properties, are being discussed [6].

While the general trend of lower thermal conductivity at high porosities seems intuitive, porosity estimates derived from thermal conductivity are currently based on an extrapolation of meteorite properties to large porosities. This is due to the fact that highly porous meteorite samples are lacking in our meteorite collections and it remains to be explored if the applied extrapolation method is physically sound. Furthermore, depending on the applied model, porosity estimates vary widely between 28% and 55% [5].

Modeling. We investigate the relationship between thermal conductivity and porosity using a numerical model of heat transport in highly porous aggregates. We model rocks on C-type asteroid Ryugu as sintered agglomerates of monodisperse spherical particles and assume that C-type boulders are mainly composed of fine-grained matrix material with few larger fragments, CAIs or chondrules, an assumption supported by sample analysis [2]. In this model, the formation of competent rocks occurs by hot or cold pressing of dust particles in the interior of the Ryugu parent body [7].

We implemented a discrete element model using the open-source discrete element method particle simulation software – LIGGGHTS® [10] to study the thermal properties of spherical particle assemblies and to derive bulk thermal conductivity [8]. To achieve the desired high porosities, we employ a sphere placer algorithm using random ballistic deposition with rolling [9]. The algorithm drops spheres at random positions from the top of the computational domain that are then made to roll once they touch another particle. This method allows for the production of particle assemblies with porosities between 44% and 85%.

Particle positions are then held fixed and physical overlap between constituent particles is treated as a tunable parameter. It is expressed in terms of contact radius normalized by particle radius in the following, where contact radius between two overlapping spherical particles is the radius of the circle of intersection between two spheres in 3D Cartesian geometry.

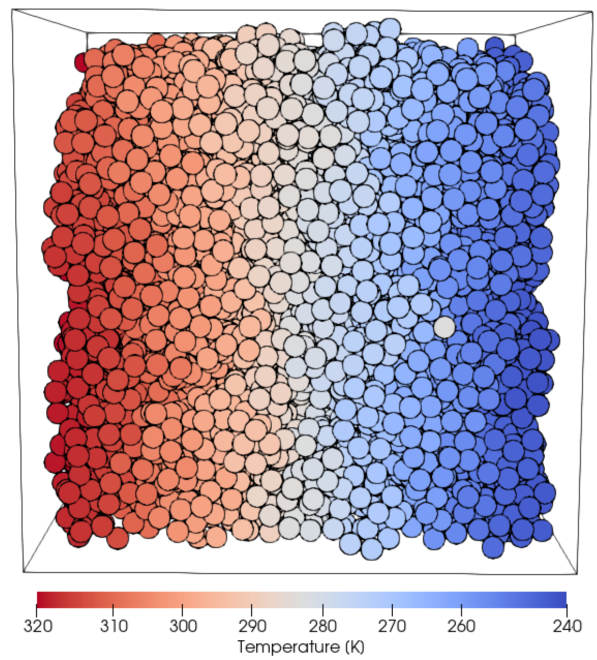

Figure 1. Temperature distribution of spherical particle beds, produced using ballistic random deposition and rolling, once the assembly attained thermal equilibrium under heat flux boundary conditions. The color bar on the bottom shows the temperature scales in Kelvin going from hot (red) to cold (blue).

Heat flux boundary conditions are then applied to the sides of the bed and calculations are performed until the assembly reaches thermal equilibrium [8]. Thermal conductivity is then calculated using Fourier's law. Figure 1 shows the temperature distribution of a typical particle bed after attaining thermal equilibrium. To study thermal conductivity of the aggregates as a function of porosity, we have produced assemblies with porosities ranging from 47% to 72%. Additionally, we also determine thermal conductivity varying the normalized contact radius between 4% to 11%.

Results. Our calculations are summarized in Figure 2. We present thermal conductivity of the different packings as a function of porosity and particle overlap, the latter of which acts as a proxy for the amount of sintering. Furthermore, currently available data on the thermal conductivity of meteorite samples as well as three theoretical models [12, 13, 14] often used to extrapolate thermal conductivity to high porosities are shown for reference.

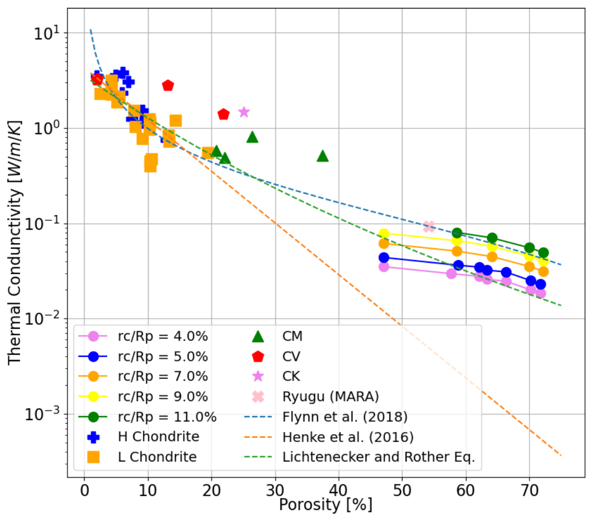

Figure 2. Bulk thermal conductivity as a function of porosity for the models considered (solid lines) is shown in comparison with data on meteorite samples (colored symbols) and the models by Flynn [12], Henke [13] and Lichtenecker [14] (dashed lines).

Our simulations are in good agreement with the model by Flynn et al. [12] if normalized contact radii of 11% are assumed. In the other models, thermal conductivity falls off much more rapidly as a function of porosity, indicating that the strength of particle contacts in these models is underestimated. Based on our microphysical model and thermal inertia determined in-situ [4], porosity of Ryugu's boulders would therefore be best compatible with values of 54.1%.

Discussion. We have developed a self-consistent model to determine thermal conductivity as a function of porosity for competent aggregates. The microphysical model is applied to the study of thermophysical properties of boulders on C-type asteroid Ryugu and enables an extrapolation of thermal conductivity to high porosities. It favors porosities towards the higher end of previously reported values, consistent with the hypothesis that Ryugu-type boulder would not survive Earth atmospheric entry and are thus underrepresented in our meteorite collections [5].

While setting up our simulations in LIGGGHTS®, we assumed the thermal conductivity of constituent particles to be 1 W/m/K. To corroborate our results, additional simulations using particle assemblies composed of particles with higher thermal conductivities need to be performed. While this is unlikely to fundamentally change the conclusions drawn here, these models will shed light on the relationship between thermal conductivity, the strength of particle contacts, and porosity. Additionally, simulations need to be extended into the low porosity regime. To this end, we will incorporate bimodal and multi-modal distributions of particles within the assembly.

While the presented results cannot explain the reported discrepancy between results obtained from remote sensing and in-situ data as compared to the analysis of returned samples, the model could be applied to the study of (micro) cracks to investigate a potential scale dependence of thermophysical properties.

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