FULL-FIELD MODELING OF HEAT TRANSFER IN ASTEROID REGOLITH: THERMAL CONDUCTIVITY RESULTS FOR MONO- AND POLYDISPERSE PARTICULATES.

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Introduction: The OSIRIS-REx mission is currently studying the surface of near-Earth asteroid Bennu, where it will collect a sample of regolith for return to Earth [1]. It is possible to infer the physical properties of the regolith, such as particle size distribution, porosity, and composition, from thermophysical measurements of the asteroid surface. The magnitude of diurnal temperature cycling of the regolith is directly related to the thermal conductivity of the regolith, which in turn is controlled by the physical characteristics of the regolith [2].

Previous interpretations of Bennu thermal inertia have relied on assumptions of a monodisperse regolith particle size [2], largely due to the fact that the thermal properties of particle size mixtures have not yet been well-studied. A small set of experimental measurements have shown that the thermal conductivity of mixtures tends to be indicative of the median particle size [3,4], which could lead to biases towards finer particle sizes in the interpretation of Bennu thermal inertia. These experimental findings should be verified more thoroughly, however.

We present a new thermophysical model for particulates where a bed of three-dimensional spherical particles is fully rendered in a finite element method (FEM) mesh framework. This type of model enables rapid and well-controlled investigations of the fundamental parameters that affect particulate thermal conductivity. Here we validate the solid and radiative conductivity components of the model and discuss plans to study the effects of particle size distribution on effective particulate thermal conductivity.

Methods: The effective thermal conductivity values of numerically constructed particulate samples are determined by formulating a steady-state boundary value problem where temperature is fixed along one side of the particulate domain and a constant heat flux is applied to the opposite side. The effective conductivity of the sample is directly related to the length dimension of the sample volume and the steady-state temperature differential between the two sides. The solid and radiative conductivity of the sample can be determined separately by selectively enabling heat transfer by surface-to-surface radiation within the model or alternatively by removing physical contacts between the spheres.

The particulate samples used in the FEM are three-dimensional beds of spheres that have been cropped to a rectangular volume. The Optimized Dropping and Rolling method [5] is used to generate a random packing of spheres with a prescribed size frequency distribution. The contacts between spheres with contact radius r_c are approximated with the addition of a cylindrical bridge with radius r_c at the contact locations. Geometry generation and meshing is accomplished with FreeCAD and Netgen.

View factors between all surface mesh elements with direct, non-obstructed line of sight are calculated in order to incorporate surface-to-surface radiative heat transfer into the model. The Intel® Embree high-performance ray tracing library is implemented in parallel to perform these calculations in a reasonable amount of time—typically less than 10 minutes, even for several million surface mesh elements. View factors are then calculated between faces using the single line integration method [6] and the Stefan-Boltzmann equation is used to compute radiative heat flux.

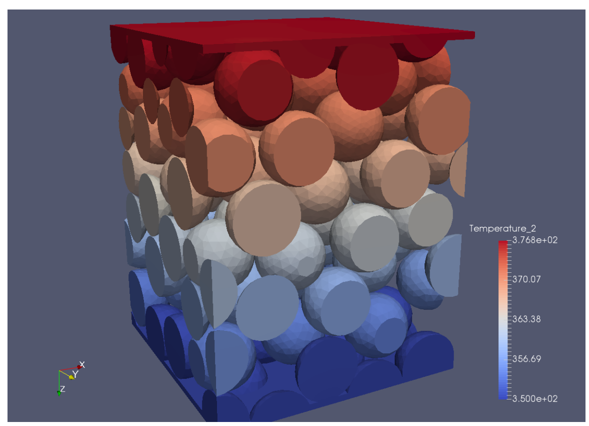

Figure 1. Example model geometry at final, steady-state heat flux temperatures. A constant heat flux is applied to the top plate while the bottom plate is held at a fixed temperature.

Validation: Numerical results for particulate radiative and solid thermal conductivity are in very good agreement with theoretical models for the thermal conductivity of monodisperse spheres (Figs. 2–4). As expected, the solid conductivity is largely controlled by the ratio of the particle contact neck radius to particle radius (r_c/R) and the average number of contacts between particles (Fig. 2–3), whereas radiative conductivity is strongly dependent on temperature and absolute particle size (Fig. 4).

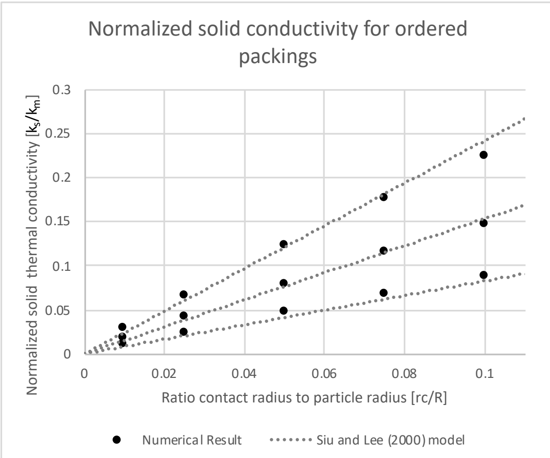

Figure 2. Solid conductivity numerical results (points) compared to theoretical predictions (lines) [7]. Packing structures from top to bottom: face-centered cubic, body-centered cubic, and simple cubic. Effective solid conductivity is normalized to the conductivity of the individual spheres (k_m).

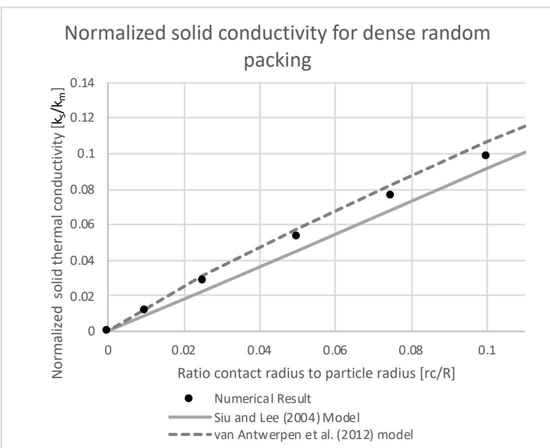

Figure 3. Comparison of numerical thermal conductivity results for dense random packing of spheres (porosity ~0.40) to values predicted by two theoretical models [8,9].

Mixtures study: The performance of the OSIRIS-REx Touch-And-Go Sample Acquisition Mechanism (TAGSAM) is well characterized for particle mixtures with power-law cumulative particle size frequency distributions, given that these size distributions have been observed on Itokawa [10]. Bennu regolith appears to also follow this type of distribution, based on preliminary results from boulder counts [11,12]. We will present initial results for a study of the effective conductivity of polydisperse particulates with different power-law exponents and minimum and maximum particle size cutoffs (e.g. Fig. 5).

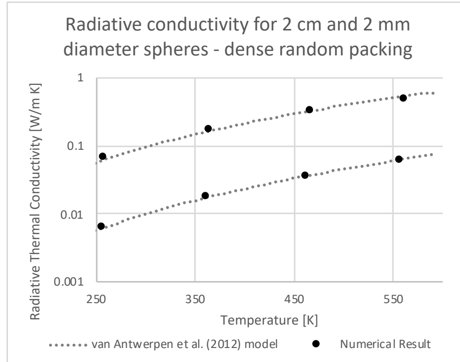

Figure 4. Radiative conductivity numerical results compared to well-validated model [9] for two mono-disperse random packings (porosity ~0.40) with spheres diameters of 2 cm (top) and 2 mm (bottom).

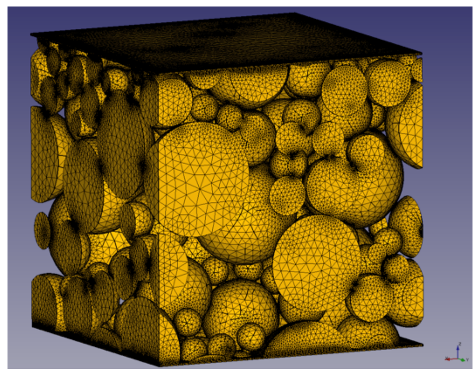

Figure 5. Example geometry and surface mesh for a particle size mixture similar to the “7c” mixtures used for TAGSAM testing [8].

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