A Numerical Method to Determine Bulk Thermal Conductivity of Randomly Packed Particle Beds

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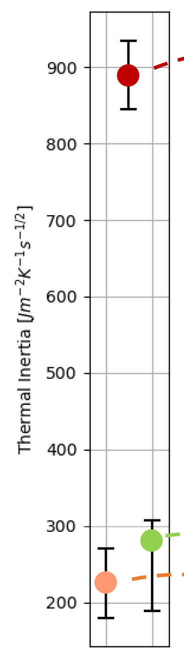
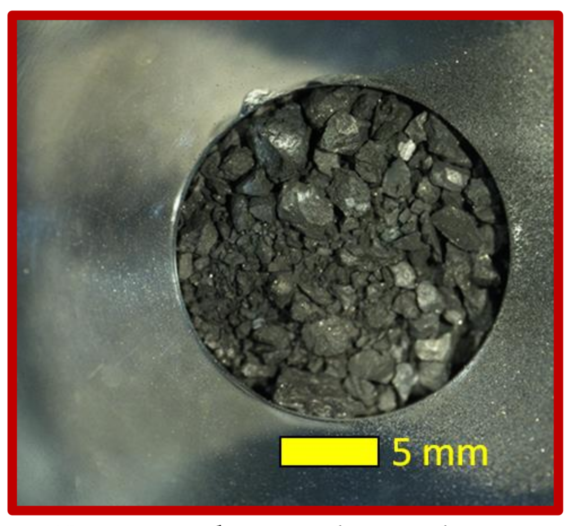
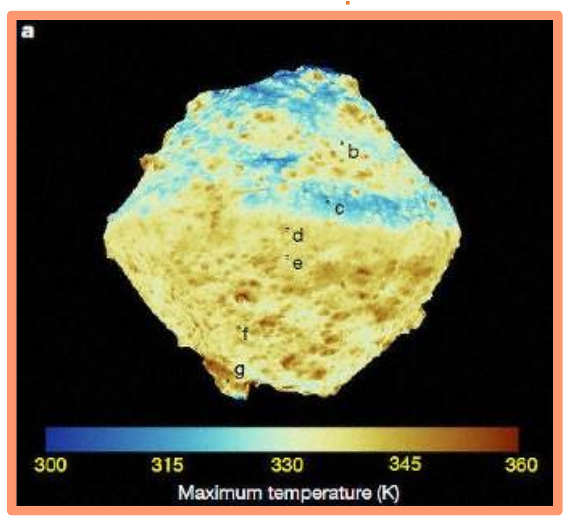
A comprehensive analysis of the remote sensing and in-situ measurements from the Hayabusa2 mission to the near-Earth asteroid Ryugu, reveals a dissonance in thermal observations [1]. This incongruency alludes to an underlying mechanics dictating thermal properties of asteroids. It has been proposed that low thermal inertias observed in-situ would be caused by high porosity of boulders in Ryugu [3], and scale dependence of thermal properties [4]. In order to expound the ideas and explain the discrepancy, we employ discrete element modelling (DEM), with the open source software package – LIGGGHTS® [5], to numerically determine the thermal conductivity of highly porous random particle beds.

Motivation:

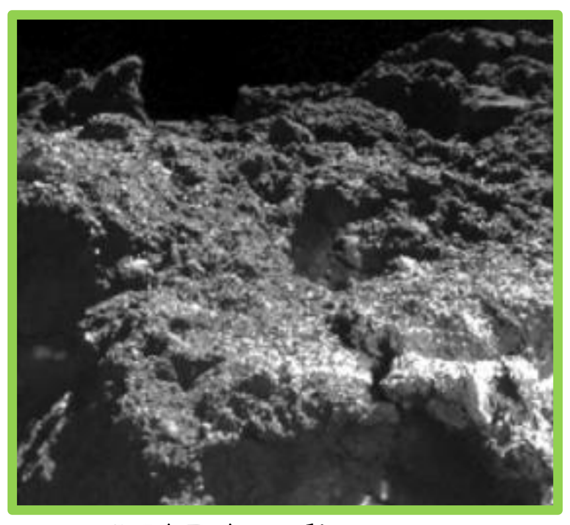




Returned sample analysis



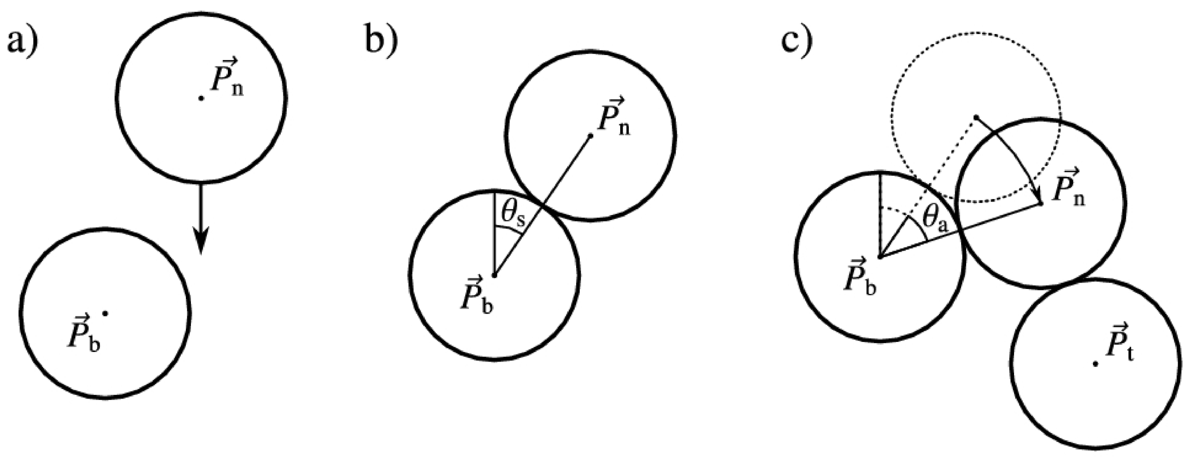
TIR thermal infrared imager (remote observations)



MARA radiometer (*In situ* observations)

Global **in situ and** ***micro scale*** **sample analysis exhibits strong contrast of thermal properties!**

Sphere-placer Algorithm:



- L. Klar *et al.* [7] describe an algorithm to produce sphere packings with porosities in range 42% to 85%
- ***Random ballistic deposition*** of spherical particles
- New particle $\vec{P}_n$ ***rolls*** along the base particle $\vec{P}_b$ by additional angle θ_a
- N_φ number of tries for the azimuthal angle

Outlook:

Another theme will be to explore the effect of ***mixing ratio*** of ***bimodal distribution*** of spherical particles on the thermal properties. Here we will setup the beds with different radii spherical particles and thermal conductivities to study the ***percolation*** of smaller radii particles in the bed for a range of mixing ratios.

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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**, 51 (2023). [3] M. Grott *et al.* Nature Astronomy, **3**, 971-976 (2019). [4] B. Agrawal *et al.* LPSC 2024 Abstract No. 1471. [5] C. Kloss *et al.* Progress in Computational Fluid Dynamics, An Int. J. **12**, 2/3 (2012). [6] N. Sakatani *et al.* AIP Advances **7**, 015310 (2017). [7] L. Klar *et al.* Granular Matter **26**, 59 (2024)

Modelling:

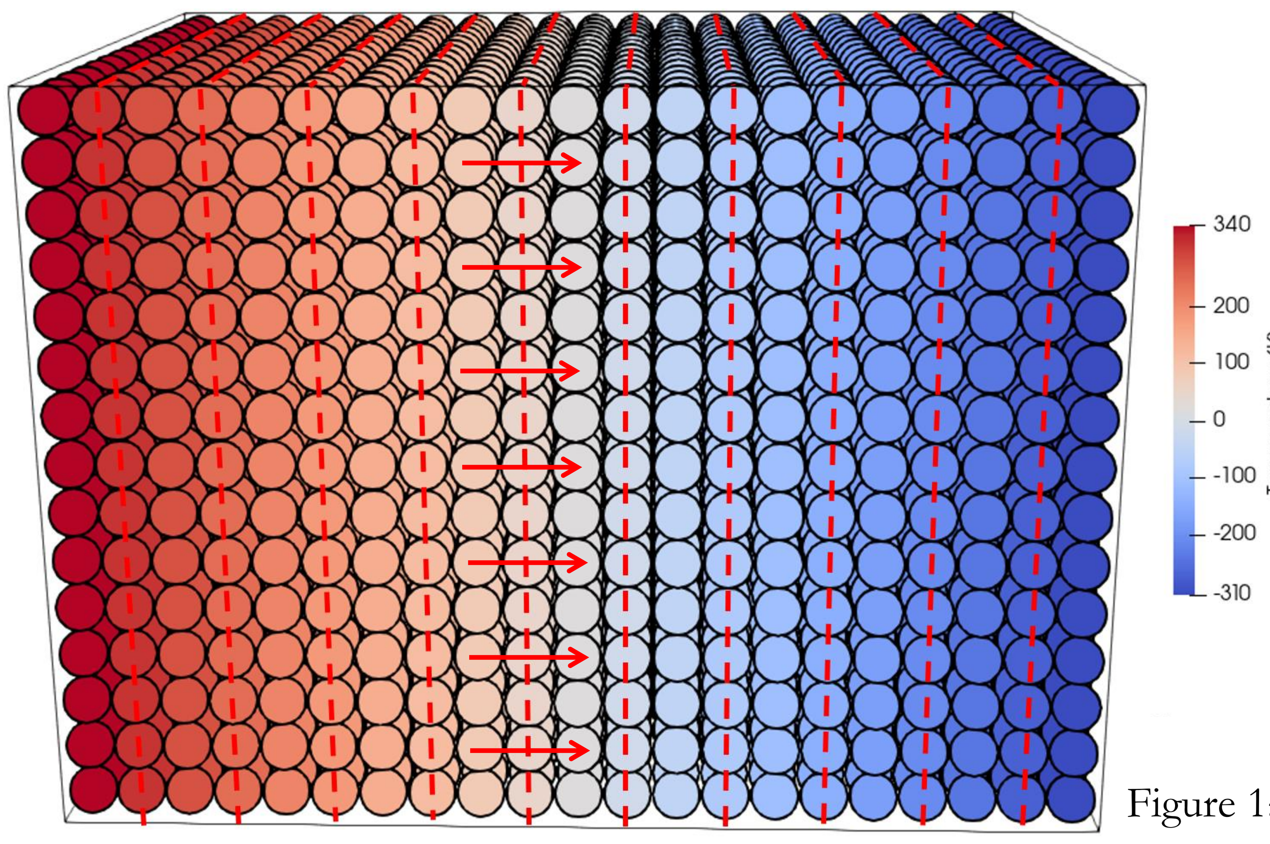

Figure 1a

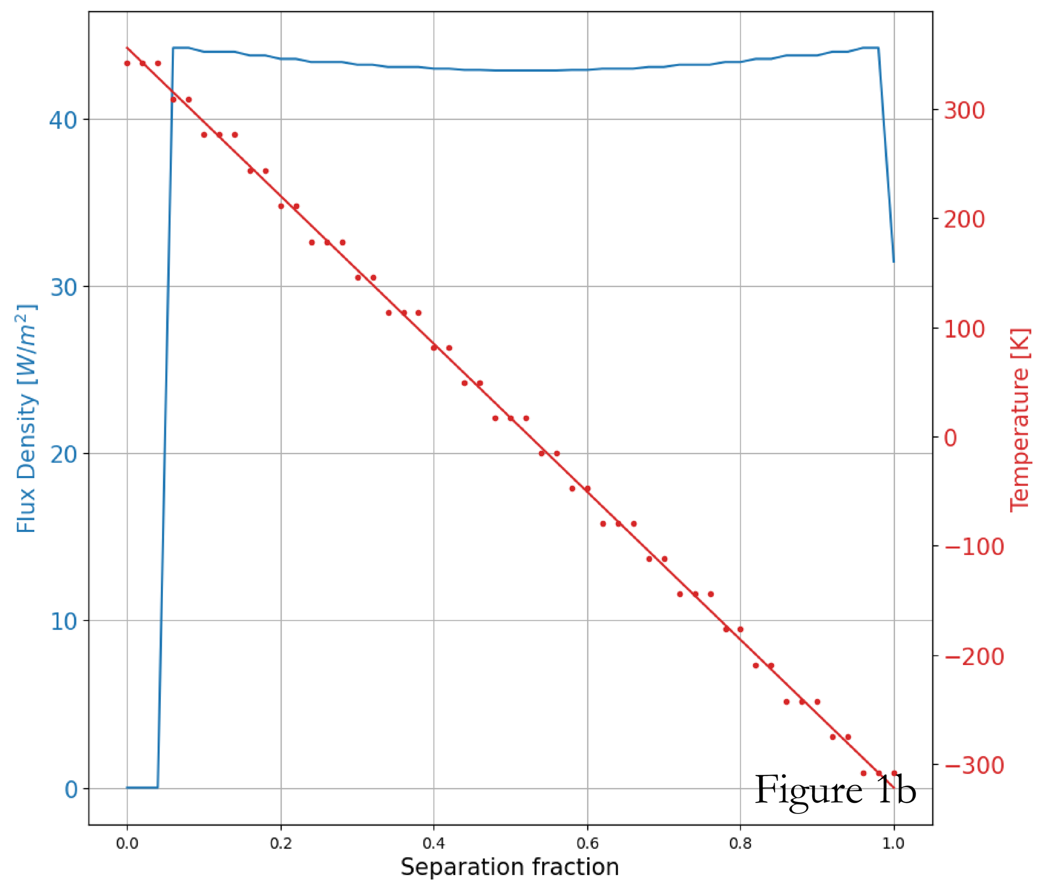

Figure 1b

The desired ***system*** of spherical particles is introduced into a simulation volume. This particle bed is subjected to flux boundary conditions i.e. the particles on the left and right are set to behave as heat ***sources*** and ***sinks*** respectively, while all the other walls are adiabatic in nature. This setup is then allowed to reach a thermal equilibrium which can be seen in the temperature profile and flux density plots. In the equilibrium state, the particle bed is segmented into ***layers*** by introducing equidistant planes normal to heat flux (shown in *fig. 1a* in a simple cubic packing for simplicity). The flux density and temperature when plotted against the ***separation fraction*** (defined as the ratio of distance of layer from the left boundary to the width of the bed) indicates the equilibrium state as shown in *fig. 1b*. Within the bulk of the particle bed, the flux density approaches a constant Q while the temperature profile acquires a constant slope $\Delta T/\Delta z$. The thermal conductivity k_{bulk} is determined from these quantities using

$$k_{bulk} = Q \cdot (\Delta T/\Delta z)^{-1}$$

Thermal Conductivity:

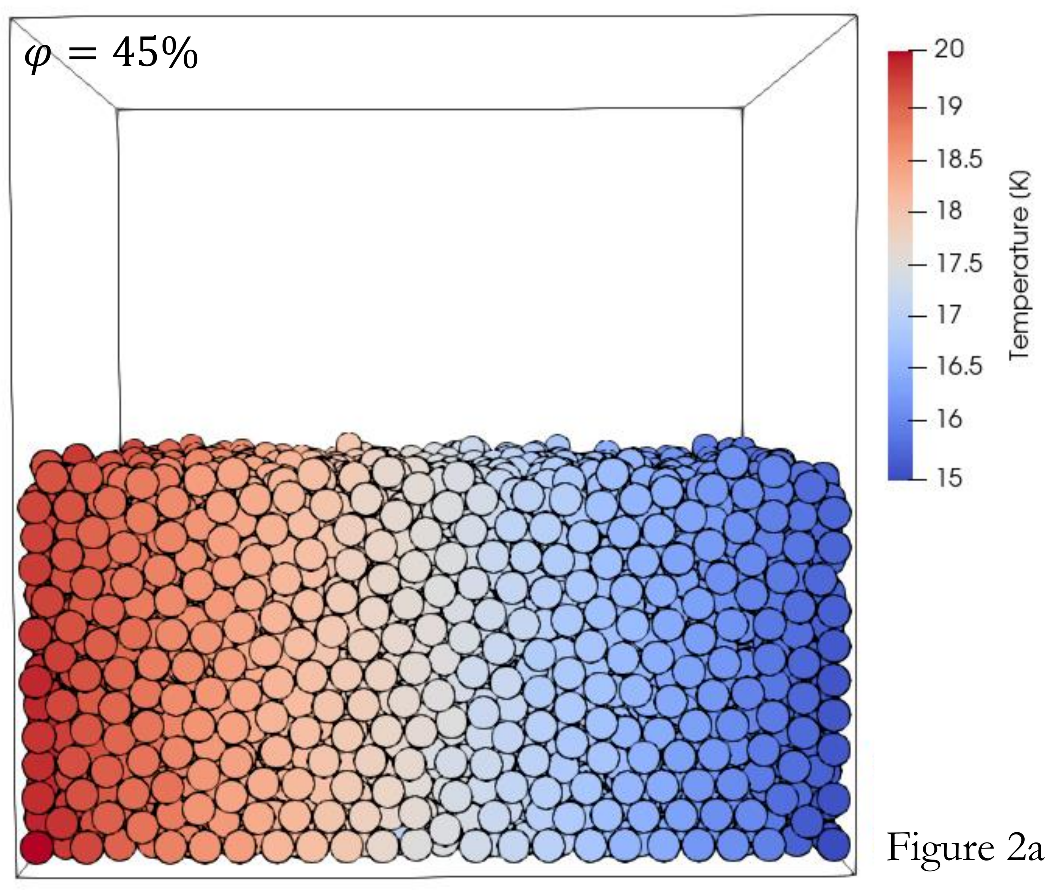

Figure 2a

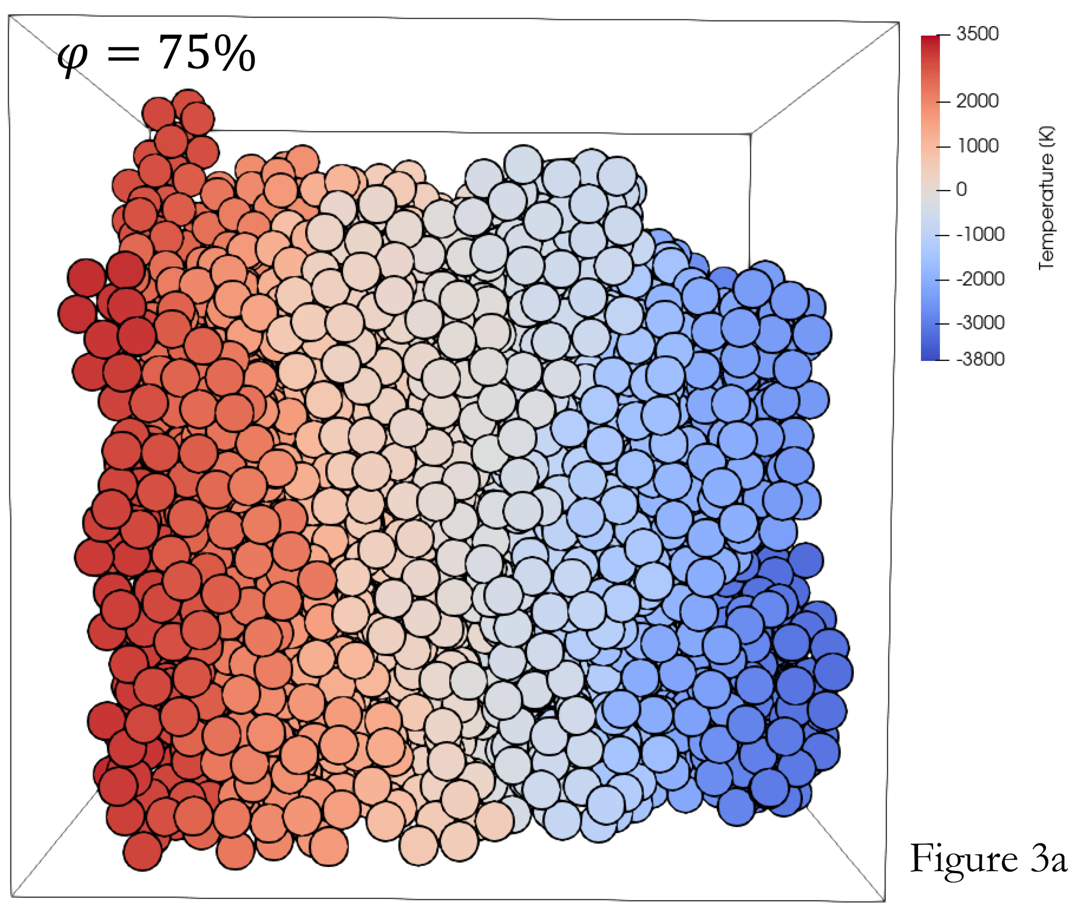

Figure 3a

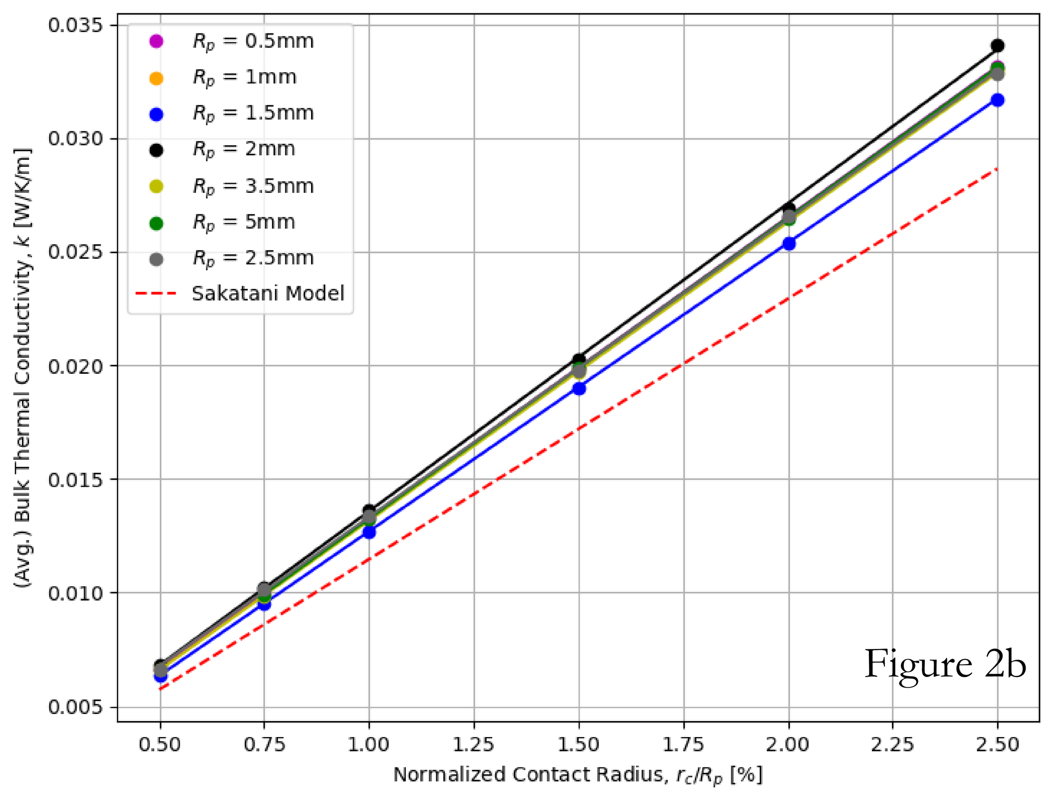

Figure 2b

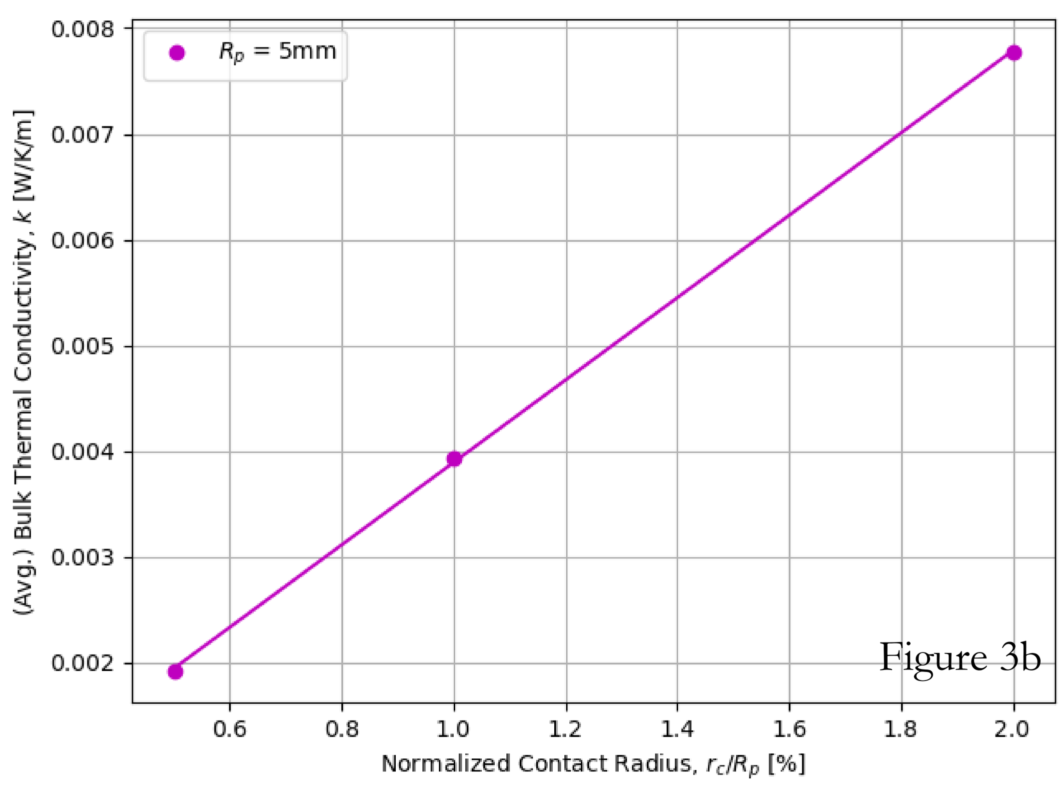

Figure 3b

With the tools ready, we produced various monodisperse spherical particle random beds. Fig. 2a and 3a show two such beds, former made from particles randomly settling under gravity while the latter produced by random ballistic deposition with rolling algorithm in [7]. Using normalized contact radius, defined as ratio of contact radius to the particle radius, as a tunable parameter we incorporated the effects of sintering at the contact points between particles. Fig. 2b and 3b are the corresponding plots of bulk thermal conductivity vs normalized contact radius. The different particle radii are each shown with a different color. We observed a good agreement between numerical and analytical models, and a slight spread in thermal conductivities as overlap increases which is ascribed to the direction of heat flow between two contact particles with respect to net heat flow (fig. 2b).

We aim to formulate a thermal conductivity model with respect to porosity focusing on high porosity regime. A library of variegated porosity beds are produced similar to that in fig 3a. Varying the normalized contact radius for the beds will produce a family of curves facilitating a more comprehensive understanding of thermal properties as a function of porosity and the extent of sintering.