Estimation of thermal conductivity using digital rock physics without segmentation: evaluation of the effectiveness for sandstones

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The temperature distribution in the deep part of the underground has some effects on forming process of underground resources, depth of epicenters, deformation of the crust, and so on. To elucidate the temperature distribution, thermal properties of the mantle, crusts, and sediments are needed in addition to temperature data of points. These days, a lot of cores are drilled and stored in many drilling projects around the world including International Ocean Discovery Program (IODP). However, there is no other way to know their thermal properties except for measurements in a laboratory. Measurements give accurate values, but it is difficult to measure the whole part of a long core or many samples in a short time because we must measure every few centimeters. Thus, another way that can analyze thermal properties without measurements is now required. It is called "Digital Rock Physics (DRP)".
DRP uses data from X-ray Computerized Tomography (X-ray CT) images and estimates the physical properties of rocks via numerical processes. Nowadays, X-ray CT images are taken soon after drilling cores, so it is easy to obtain data of them. So far, there are many previous works estimating other physical properties like resistivity, elastic wave velocity, etc. but few works about thermal properties exist. In previous works estimating the thermal conductivity, X-ray CT images were separated into two segments: mineral and pore phase. That is named the "Segmentation method" which can be applied to only several types of rocks and estimation values may differ by wrong segmentation.
To establish a new method that can estimate the thermal conductivity of various kinds of rocks with high accuracy, in this research, the thermal conductivity of core samples of sandstones was estimated without segmentation (called the "Segmentation-less method"). The output values were compared with measurement data by the Hot-Disk method and consequently, the effectiveness of the Segmentation-less method was suggested.
This research consists of two parts: creating digital rocks, and a numerical process. In the first part, at first, a three-dimensional array of CT numbers was created using X-ray CT images. Then, by determining specific voxels called "pseudo-targets" that were defined as pure minerals or pore space, a continuous function of CT number was derived for calculating the density of each voxel. After calculating, the density of each voxel was converted into the porosity based on the monomineralic assumption. In addition, the thermal conductivity and the specific heat were calculated at each voxel. Note that the calculation of thermal conductivity was performed via four types of equations from "mixing models": the harmonic mean, the arithmetic mean, the geometric mean, and the square root mean. That means four digital rocks were created.
In the second part, three-dimensional thermal conduction was numerically calculated in digital rocks. Assuming walls that have fixed temperature by Dirichlet boundary conditions and adiabatic walls by a Neumann boundary condition, the heat conduction equation was solved by the finite difference method. Then, the thermal conductivity of the whole inspection area was calculated by analyzing the temperature distribution at the steady state. Four values of the thermal conductivity from four patterns of digital rocks were all compared with the measurement value by the Hot-Disk method.
As a result, it is concluded that the geometric mean gives the most valid model and that was the case with both the dry and the water-saturated conditions. In DRP, the estimating values depend on the CT number of each voxel and each voxel has just one CT number although there are two or more phases in the area of one voxel. Since the geometric mean assumes that several components are randomly oriented and

distributed, it is considered that the geometric mean is the most suitable model in applying DRP to sandstones.

Keywords: Digital Rock Physics, Segmentation-less, X-ray CT