Thermal Conductivity of Synthetic Materials Across Varying Saturation States

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Introduction: In subsurface environments, geological formations retain moisture and fluids through infiltration across the Earth's crust, affecting processes such as geothermal energy extraction and gas storage, rendering the assessment of the thermal conductivity and fluid saturation relationship paramount.

Synthetic materials with known compositions and porosities are standardized benchmarks to investigate these phenomena. They offer a systematic framework to understand the behavior of natural materials under diverse conditions. However, despite their utility, the characterization of these synthetics remains sparse, with challenges ranging from the accessibility of effective thermal conductivity measurements to existing methodologies inadequately addressing the influence of saturation levels on thermal properties.

This research addresses these gaps by characterizing the porosity, permeability, and thermal conductivity of micro- and nanoporous synthetic materials across different saturation states. These workflows are designed to enhance the accuracy and reliability of models applied to complex, heterogeneous natural materials.

Methods: Synthetic material samples are initially prepared in an unsaturated state. Porosity and permeability are measured using a pycnometer and imbibition, respectively.

Thermal conductivity is determined using a Modified Hot Plate Method. A hot plate is set to a constant temperature, and a custom 3D-printed holder encapsulates the sample. The holder features a heat-resistant casing enclosing a known insulator around a sample wrapped with ceramic fiber tape. Thermocouples embedded within the holder and connected to a data logger (CR1000X) measure temperatures at the center of the sample's base and top.

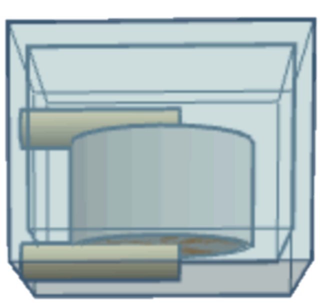

Figure 1. 3D-printed Design for Thermal Conductivity Assessment

Saturation of the samples with fluid is achieved using vacuum saturation for each designated level: 20-25%, 50-55%, 70-75%, and 95-100%. The determination of porosity, permeability, and thermal conductivity are repeated for a given saturation condition.

Results: The current study focuses on theoretical modeling of the effective thermal conductivity of unsaturated glass frits. The Fourier-Biot equation was employed to simulate this heat transfer.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(k.r\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \phi}\left(k.r\frac{\partial T}{\partial \phi}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+q_v=\rho c_p\frac{\partial T}{\partial t}$$

Figure 2. Fourier-Biot equation

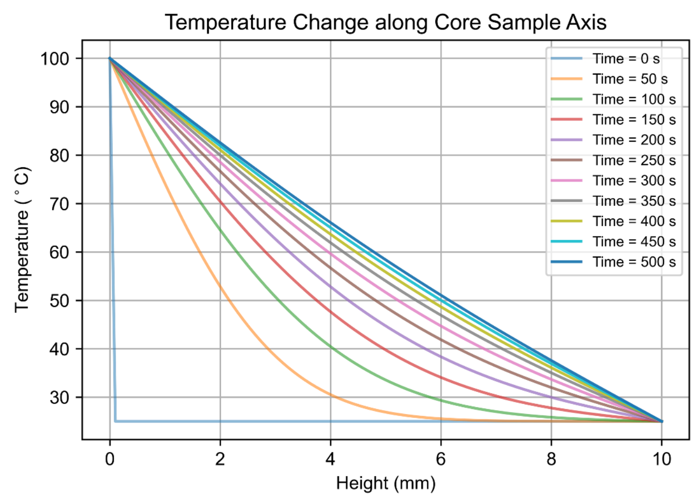

Figure 3. Theoretical Solution: Temperature Change along the Core of Unsaturated Porous Glass Frit

Future experiments will compare the saturated results against a benchmark–the theoretical unsaturated solutions. This framework, applied to variations in pore size and distribution within a material subset, aims to characterize the effective thermal conductivity as a function of saturation for the specific synthetic type and class studied.