Effective thermal conductivity of open-cell ceramic foams

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Abstract

Cellular materials (also known as foams) are a source of interest in many thermal engineering applications, as their properties can be tailored to both heat exchange and heat insulation demands through their unique microstructure. In particular, ceramic foams can have service temperatures up to and above 1000°C thanks to their thermal stability. As accurate experimental characterization under service conditions can be highly challenging, numerical modeling offers a versatile way to predict and optimize the effective properties of foams. The present study presents improvements in numerical methods to compute the effective thermal conductivity from realistic pore-scale models of open-cell ceramic foams, validated with a case study of heat conduction modeling in highly porous alumina foam samples.

While early analytical models of foam conductivity were based on simplified unit cell models, the development of micro-computed tomography (µ-CT) has led to increasingly realistic numerical models that take into account the influence of fine microstructural characteristics. One could directly use the reconstructed tomographic scans to compute the effective foam properties. However, most numerical homogenization techniques require the assumption of geometrical periodicity, which rarely exists in real foams. Various methods have thus been employed in past work to generate of periodic representative volume elements (RVEs) based on relevant morphological parameters extracted from the tomographic scans. This latter approach also has the benefit of allowing easy exploration of a wide range of realistic microstructures for optimization purposes. However, the fascinating variety of foam morphologies observed in nature means that the choice of RVE generation technique remains an open problem.

The strategies discussed in the present work aim to improve numerical predictions for both non-periodic structures and digitally generated periodic RVEs. Using reconstructed tomographic scans of an alumina foam sample, the effective thermal conductivity is first computed with a mixed boundary condition that is demonstrated to provide accurate predictions in non-periodic geometries. Periodic RVEs of the studied foam sample are then generated using two state-of-the-art approaches: the first shapes the void phase with a sphere-packing-and-inflation algorithm aiming to simulate bubble physics, while the second grows the solid phase from the edges of a stabilized Laguerre-Voronoï tessellation. The generated RVEs are validated by comparing the morphological parameters and computed effective conductivities of the virtual foams with those of the real foam. The results of this study provide guidelines towards more accurate numerical predictions of the effective properties of open-cell foams.

Keywords: Foam, Microstructure, Thermal Conductivity, Homogenization, Finite Element