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Prediction of the thermal conductivity of porous building materials with nanoscale pore size distributions

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Porous materials find frequent use in numerous thermal applications, offering a strong reduction of the total heat flow. Typical applications can be found in the automotive industry and aerospace engineering for the protection of sensitive components, but also in the building industry where heat losses through the opaque building components still account for a large part of the needed heating energy. Therefore, recent research activities have focused on the development of several new types of porous materials, i.e. vacuum insulation and aerogels, showing strongly reduced thermal conductivities compared to conventional insulating materials. Their improved performance is mainly attributable to their microstructure, composed of pores and matrix walls with nanoscale characteristic dimensions, rendering the classic Fourier diffusion heat law no longer valid. Indeed, at decreasing length scales and pressures, the heat flow behavior is known to shift to the Knudsen diffusion regime, resulting in reduced conductive heat transfer through the gaseous and the matrix phase. A more thorough understanding of the impact of these microstructural parameters on the total heat flow through the material could hence lead to a significant optimization of insulating materials. However, current numerical studies are often based on simplified analytical models and microstructures or focus on only one form of heat transfer.
In this study, a recently implemented pore-scale model for studying heat transfer in conventional cellular porous materials is expanded for studying materials with nanoscale features or reduced gas pressures. The model is based on 3D voxel images of the microstructure, thus incorporating the true microstructural parameters. The nanoscale ballistic behavior of the energy carriers in the gaseous phase is modelled by defining local thermal conductivities based on the kinetic theory. The reduced local effective mean free path is calculated using several geometrical parameters, considering both the shape and the size of the pore structure. Hence the model allows for an efficient simulation of the heat flow through the material, while implementing the Knudsen diffusion locally at the pore scale. The model is verified using existing analytical models and simple microstructures, showing good agreement. Finally, the model is used to make a preliminary study on the relative impact of several microscale parameters, showing the potential improvement of these new materials compared to conventional materials.

References

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