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Implementation and validation of a 3D image-based prediction model for the thermal conductivity of cellular and granular porous building blocks

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HIGHLIGHTS

- A framework to predict the thermal conductivity of porous materials is introduced.
- It allows performing pore-scale thermal simulations on 3D images of microstructures.
- The verification with analytical reference solutions shows very good performance.
- The experimental validation demonstrates the accuracy of the prediction framework.

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ABSTRACT

Porous building blocks are increasingly being used in the building sector, as they offer a relatively high thermal resistance because of their porous microstructure. A clear understanding of the relation between the material's microstructural properties and effective thermal conductivity is still lacking though, impeding a correct analysis and design of existing and new porous building blocks. Therefore, this paper presents a 3D model framework to study the heat transfer through both cellular and granular porous building blocks, performing simulations directly at the pore scale. A 3D voxel-grid representation of the pore structure is adopted, allowing to study both virtually generated materials and actually available materials. The accuracy and the impact of the grid parameters is verified on a set of elementary microstructures, demonstrating a good performance when using adequate settings. The thermal conductivity simulation framework is validated against experimental measurements on two highly different porous materials: a low-porosity granular sintered glass filter and a highly-porous cellular-granular acoustic absorber. Comparison of simulation outcomes with experimental results confirms the good performance of the model, indicating its potential to evaluate and optimize the thermal conductivity of porous building blocks.

1. Introduction

1.1. Background

Heat transfer through opaque building components constitutes an important part of the total energy consumed by residential buildings. Insulation materials like mineral wool or several types of plastic foams are therefore often used to improve the thermal resistance. Their highly-porous nature effectuates indeed very low thermal conductivities, but on the other hand also relatively poor mechanical properties. Hence, they require to be used in combination with load-carrying elements like solid bricks or concrete slabs. Porous building blocks, on the other hand, aim to combine both load-carrying and thermal insulation capacities [1–3]. Well-known commercial variants are cellular glass or cellular concrete. Typically, these blocks come as large brick-like elements, usually available in different thicknesses, sizes and densities. Hence, they provide alternative design options and easy on-site construction while reducing the heating and cooling energy requirements [4–6]. Furthermore, porous building blocks show great potential for upcycling secondary materials: several studies illustrate the production of porous building blocks including or based on e.g. slags or recycled ceramics [1,7–9]. Such valorization provides increasing economic return while reducing industry-generated waste streams. However, due to increasingly stringent

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Nomenclature

Roman

T	Temperature (K)
d	Distance between opposing pore cell walls
q	Heat flux (W/m^2)
V	Volume (m^3)
L	Length of cube side (m)
f_V	Pore volume distribution

Abbreviations

ETC	Effective thermal conductivity (W/m K)
SC	Simple cubic
BCC	Body-centered cubic
FCC	Face-centered cubic
Cel.	Cellular
Gran.	Granular
MIP	Mercury intrusion porosimetry
Exp. Meas.	Experimental measurements
CT	Computed tomography

Greek

λ	Thermal conductivity (W/m K)
ε	Emissivity (–)
σ	Stefan-Boltzmann constant $\left(5.67 * 10^{-8} \frac{W}{m^2 K^4}\right)$
γ	Pore shape factor (–)

Subscripts

rad	Radiative
max	Maximum

energy requirements, a further reduction of the heat flow through these materials is needed to improve their performance and boost their application [10].

The heat transfer through porous materials is often described at the macroscale using Fourier's heat conduction law making use of the material's effective thermal conductivity (ETC). However, as illustrated in Fig. 1, the total heat flow through the material originates from the complex interaction of several heat transfer mechanisms occurring at the microscale: thermal conduction through the solid matrix and the gas-filled pores, natural convection in the gas-filled pores, and radiation between the pore walls. Microstructural properties like the porosity and the matrix connectivity majorly affect each of these microscopic heat transfer mechanisms and accordingly also the macroscale effective thermal conductivity. Research on modelling and understanding this close relation is hence crucial in the development of improved building blocks.

1.2. Literature and state-of-the-art

Several techniques have already been employed to characterize the impact of the microstructural properties on the ETC. These can roughly be classified in three categories: experimental, analytical and numerical studies. A non-exhaustive overview is discussed in this section.

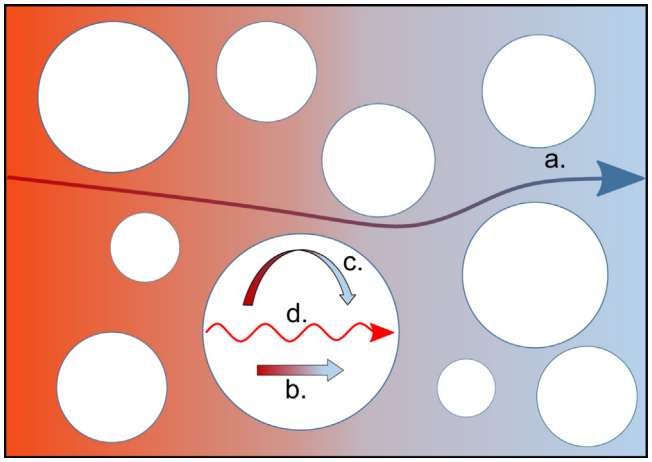

Fig. 1. Overview of heat transfer mechanisms at the pore scale: (a) matrix conduction, (b) gaseous conduction, (c) natural convection and (d) thermal radiation.

Experimental studies, firstly, allow for a direct and reasonably accurate characterization of the thermal and microstructural properties of a porous material. Examples are the studies of Benoit-Ali et al. [11], Coquard et al. [12] and Smith et al. [13], who investigated a set of porous ceramics and metal foams with varying porosities, pore size distributions and matrix constitutions. Via detailed measurements of their macroscopic ETC, they studied the impact of, for example, the matrix conductivity or the spatial distribution of pores in the matrix. A similar study was performed by Goual et al. [14] on insulating clayey aerated concrete samples, while Aurangzeb et al. [15] conducted measurements on a set of limestone samples. Their results again clearly show the considerable effect of porosity and matrix conductivity on the ETC. While such experimental investigations provide interesting insights in the combined impact of these microstructural properties, a detailed study of the isolated influence of specific parameters is very difficult. Furthermore, the experimental preparation and measurement of porous samples is often expensive in time and cost. The inherent limitation to already-existing materials finally yields insufficient versatility to study and design new porous materials.

A second class of studies investigate the thermal behaviour of porous materials by developing analytical relations linking the ETC to a number of microstructural parameters. Excellent overviews of some analytical models can be found in Progelhof [16], Collishaw et al. [17] and a chapter by Singh [18]. The proposed relations are usually acquired through either theoretical considerations of the geometry and heat flow, or through the extrapolation of experimental measurements. Two well-known examples of the theoretical type are the series and parallel models attributed to Wiener, giving the absolute upper and lower bounds for the ETC. In this case, the analytical prediction formulas are derived using a simplified serial or parallel organization of the matrix and gas phase. Similarly, other often-cited analytical-theoretical models like the models of Maxwell [19], Bruggeman [20] and Landauer [21] are usually deduced using some sort of simplification of the pore structure geometry or the present heat transfer mechanisms. Hence, although being very fast, their thermal conductivity prediction ability is rather indicative and lacks accuracy. The empirical type of analytical models provides increased accuracies by including an empirical factor that should be derived through experimental measurements. Well-known examples are the model of Asaad [22], Pande-Chaudhary [23] or Kunii-Smith [24]. Obtaining this empirical factor is cumbersome though and limits the applicability of the model to a certain class of existing materials.

Numerical models finally show great potential for a more thorough understanding of the material's thermal properties [25,26].