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An intermingled fractal units model to evaluate pore size distribution influence on thermal conductivity values in porous materials

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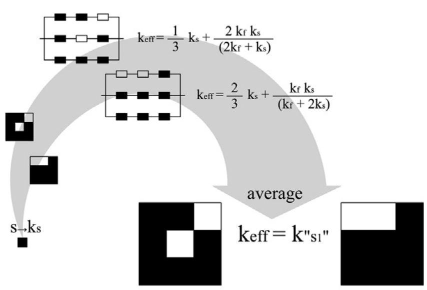
HIGHLIGHTS

- An intermingled fractal units model is presented based on Sierpinski carpet.
- Model originality lies in being able to simulate any type of real microstructures.
- By turning model into electrical pattern it is possible to have thermal conductivity.
- IFU model evaluates pore size distribution influence on thermal conductivity.

GRAPHICAL ABSTRACT



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ABSTRACT

The modeling of the microstructure of the materials is growing. Several studies have shown that fractal geometry is a tool that can replicate and investigate the nature of the materials and their physical properties. In particular, many of these are related to the porous microstructure in its different aspects. The influence of the pore size distribution has been little investigated yet. In this work the overall issue is to show a model for the calculation of thermal conductivity for porous materials with different pore size distribution, but with constant porosity. The intermingled fractal unit model used, is characterized by a close relationship with real microstructure and in prevent studies it has been possible to find good correlations with the experimental data.

1. Introduction

The use of fractal geometry, as a tool for the study of porous microstructures, is well established in the scientific literature [1–5]. The fractal concepts are used to derive analytical expressions from which to obtain some physical quantities as well as the increasing capacity to simulate the porous microstructures in all their facets: volume fraction of voids, specific surface area, pore shape and size distribution pores. In this regard the recent applications of concepts and methods related to Fractal Geometry become quite important. Buiting et Al. studied porosity-permeability relationships for a tortuous and fractal tubular bundle [6]. Xu et Al. indicated that the geometrical parameters like porosity, fractal dimension for pore size distribution and tortuosity fractal dimension, have significant effect on the multiphase flow through unsaturated porous media [7]. Zheng et al. [8] proposed a model for the pressure-driven gas flow flux affected by temperature, it is expressed as a function of porosity, the fractal dimensions and temperature. Eric et al. [9] studied heat flux performance for a prototype wick structure fabricated from compressed carbon foam when used with a Loop Heat Pipe (LHP) containing a fractal-based evaporator design. Atzeni et al. [10] measured fractal dimension, derived from pore size distribution, to correlate it with mechanical properties of vesicular basalt used in prehistoric buildings. Jin et Al. equated the fractal dimension of air

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voids size-distribution and the durability factors of concrete [11]. In Arandigoyen et al. [12], microstructure of blended mortars is studied taking into account porosity, pore size distribution and surface fractal dimension, meanwhile Diamond et al. [13] have shown that pore systems of concrete could possibly present fractal characteristics.

Fractal geometry is also able to describe heat transference process and analytical expression can give thermal conductivity value related to experimental data. In fact Huai et Al. generated several types of fractals to model the structures of porous media and to simulated heat conduction by the finite volume method [14] and lattice Boltzmann method [15,16], while Pia et al. [17] studied the effect of microstructure on lightweight concrete prepared from clay, cement, and wood aggregates and on fractal model microstructure [18]. Xiao et al. [19] proposed a model distinctly related to the thermal conductivities of the base fluids and the nanoparticles, the average diameter of nanoparticles, the nanoparticle concentration, the fractal dimension of nanoparticles and physical properties of fluids. A good agreement between the proposed model predictions and experimental data was found. Zhou et al. [23] adopted the fractal theory to establish a geometric model of the aquifer, which helps with the analysis of the heat transfer mechanism in an irregular configuration, and derives a correlation of the overall thermal conductivity from the thermal resistance structure. In this paper fractal concepts are used to verify the influence that a certain configuration and porous microstructure has on the properties of the material [20,21]. To do this it is first necessary to convert the experimental data in a fractal pattern and subsequently perform a "virtual" experiment on it. In recent years some authors have shown that through a fractal procedure, known by the acronym IFU (Intermingled Fractal Units) both fractal and non-fractal types of pore size distributions can be simulated. The versatility of this model is allowed by the use of different fractal figures combined together [17,22].

Thermal conductivity is of particular interest when it comes to metal foams [23,24]. The heat flow is influenced by the low volume fraction of the solid phase, by the conductivity of the gas enclosed, by the size of the cell and pores, by pore size distribution, etc [25]. Regarding these materials the latter characteristic is often overlooked especially given the control of the pore size distribution it's still very difficult to achieve in the production phase for some materials, and even though the range of the rays, on which porosity develops, is not often excessively wide, it can surely influence these properties [16,26,27]. For this reason, an approach similar to the one displayed in this paper can be proposed for the study of thermal conductivity in metal foams. Thus by analyzing their sections and building a network of resistors in series and in parallel, a prediction on that physical dimension could certainly be made. There are number of studies in the literature on several models of metal foams and their hierarchical structures [25,28]. These are used to determine mechanical characteristics and thermal ones. It would therefore be useful to also calculate their thermal characteristics using an approach similar to the one proposed in this article. The ability to predict these quantities starting from the geometric organization of the microstructure could represent a real step forward especially when it comes to assess experimental measurements which are often hard to interpret. It is also very hard to determine those factors which in turn will determine a variation of the values of the measurement itself.

In a former article [29], it was noted how the IFU and the fractal procedure are able to get some values of thermal conductivity which are very similar to those obtained experimentally. An IFU procedure will be used in order to correlate the variation of the values of thermal conductivity with different pore size distributions.

2. Basic concepts of fractal geometry and its applications to materials technology

It is well known that in the past, research focused on the study of regular sets and functions that have been well described using forms which were defined by Euclidean geometry.

However, the results are not always sufficient to respond to the treatment of systems that appear to be "complex" ones. In fact, in reality, from the forms of nature to the dynamics of some physical phenomena such as turbulence, the processes are never regular and simple, so it sometimes becomes necessary to study using "special" means, such as fractal Geometry. Fractals are geometric figures that have several features that distinguish them from ordinary figures: (a) they have a dimension that can be non-integer (fractional, fractal); (b) they are obtained by an iterative procedure according to a certain factor, and (c) they have a fine and intricate frame; their development covers a wide range of sizes and this grants high detail even at smaller scales, (d) they are figures that have all their parts similar to the whole (self-similarity), and (e) They are not easy to be described with mathematical-geometrical methods in use. These properties are typical of deterministic fractals, namely, those figures that are obtained through a number of strict construction processes.

In Fractal Geometry figures can have a fractional dimension. This concept is quite innovative, but it can be easily illustrated through an example: Consider a sheet of paper, its characteristics lead us to equate it to a surface, however, if we started to bend it would partially occupy a three-dimensional space and then its dimensions won't be that of a surface or that of a volume, but between 2 and 3. Many fractals may be constructed using the iteration procedure. For example, the well-known Sierpinski carpet is obtained by repeatedly removing squares from an initial square of unit side-length. While the number of iteration increases, the geometrical structure is fine, highly intricate and detailed at all scales (Fig. 1). Another characteristic of fractals is that methods and numerical calculus of classical geometry are not suited for studying them [30,31]. In reality, as there are no objects that correspond to spheres, cylinders, cubes and "perfect" prisms, not even the perfect Fractals (deterministic) exist. For this reason the model must therefore be considered as a descriptive model which is able to get closer to the irregularity of the real forms.

3. IFU configuration to obtain pore size distribution model

The intermingled fractal unit model was used in order to represent some of the most frequent pore size distributions in natural materials and advanced ones. Five different cases (A, B, C,

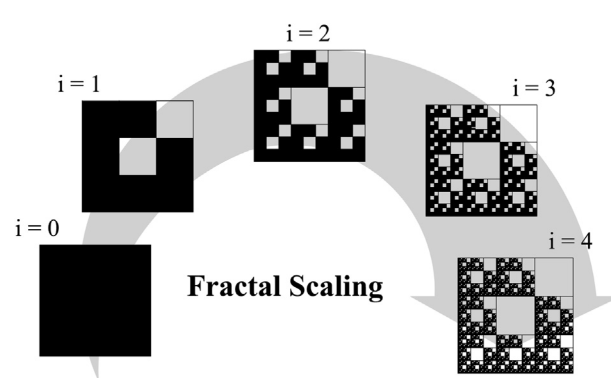

Fig. 1. Example of fractal scaling applied to a Sierpinski carpet with $D_f = 1.77$.