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Electromagnetic properties of model vitreous carbon foams

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A B S T R A C T

This paper addresses the relationship between structural and electromagnetic (EM) properties of model vitreous carbon foams, i.e., presenting different porous structures in terms of bulk density, cell size and connectivity, while having the same composition and the same carbon texture. EM properties were investigated over a wide frequency range, from 20 Hz up to 250 THz. The bulk density is the main parameter controlling the EM behaviour up to ~50 GHz, as no change was found by varying other structural parameters such as cell size or interconnectivity in such frequency range. At low frequency, foams behave similarly to metals and, when the density increases, the reflection increases and the absorption decreases. The behaviour changes above ~50 GHz, absorption becoming the main mechanism. For cellular foams, transmission and reflection tend to be negligible in the infrared region, and behave like black bodies. However, reticulated foams present non-negligible transmission that increases with cell size. Resonance phenomena were observed for reticulated foams between about 0.2 and 3 THz. A simple model considering the fundamental mode TE_{10} of a rectangular waveguide whose largest dimension was the average cell diameter was proposed to predict minima and maxima of these resonances.

1. Introduction

This article is part of a large experimental study dealing with the physical properties of model vitreous carbon foams as a function of their porous structure. These materials are all made of the same vitreous carbon as evidenced in Ref. [1], and present very different bulk densities and cell sizes which are not correlated with each other. These special features allow for the first time accurate studies of physical properties of carbon foams as a function of their porous structure, hence the name “model foams” they were given. Mechanical and acoustic properties were already analysed in Refs. [2] and [3], respectively. Since these foams are made of vitreous carbon, they are electrically conducting. The electromagnetic (EM) properties of those carbon foams with very different structures were then thoroughly investigated here, in a very broad frequency range.

Details of the preparation and of the in-depth physicochemical and structural characterisation of the present model vitreous carbon foams have been extensively given in our former papers [1,2]. In the latter, more than 62 kinds of carbon foams, obtained through the preparation of 16 different types of formulations, were presented. Most of them were cellular vitreous carbon (CVC) foams, i.e., presenting more or less spherical cells connected with each other through more or less open (i.e., perforated) cell walls. In the following, such openings between cells are called “windows” (see Fig. 1). In addition, other carbon foams were prepared by resin templating of polyurethane foams, and were therefore called reticulated vitreous carbon (RVC) foams. Examples of CVC and RVC foams are presented in Fig. 2, in which the difference of porous structure can be easily seen.

Several studies have been published about EM properties of porous media and foams [4–18]. This is a rather recent topic, and the interest is growing due to the exponential use of electronics in our everyday life. Indeed, materials such as carbon foams can be used for electromagnetic interference (EMI) shielding, either for protecting instruments from interferences that may come from outdoor, or for avoiding electromagnetic emissions from electric appliances. Composites mainly based on carbon nanotubes in a polymer matrix are widely studied for this type of applications, but

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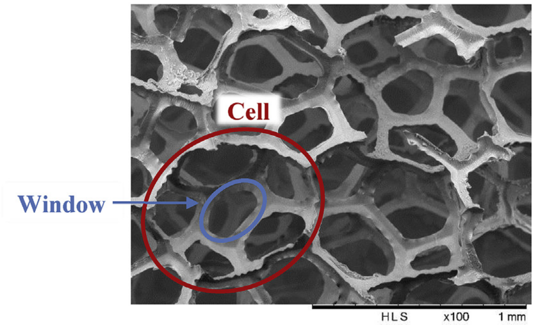

Fig. 1. Schematic structure of a reticulated carbon foam, emphasising the difference between cells and windows (i.e., holes connecting the cells). (A colour version of this figure can be viewed online.)

carbon foams were found to have much higher conductivities [5], strong EMI shielding in the microwave range, and high dielectric losses in the radiofrequency range [10,11,13]. Various studies also showed that the EM properties of these carbon foams can be optimised by modifying their structure [5,13].

In Refs. [4–6], tannin-based carbon foams of different densities (and cell sizes) were analysed from 20 Hz to 37 GHz. In the following, those materials were called “standard CVC foams”; their cell size increased when the bulk density decreased [19,20], just as in most other rigid foams. Their properties were compared with those of the present model carbon foams, i.e., having controlled cell size at a given density, or vice-versa, unlike the former “standard CVC foams”.

For standard CVC foams, both dielectric permittivity [4,6] and electrical conductivity [4,21] in the quasi-static regime were high and increased with bulk density according to power laws. Significant electromagnetic interference shielding efficiency (*EMI SE*) was also found at microwave frequencies for all produced samples, and EMI shielding was shown to increase with density (which was always correlated with the decrease of cell size for these foams). The DC conductivity, analysed between −248 and + 227 °C, decreased with temperature according to Mott's law during cooling but the carbon foams still remained opaque to the microwave radiations. Moreover, it was shown [8] that two approaches can be used to model the EM properties of these foams in the microwave range, either based on a homogenisation procedure and considering the foam as a single layer of homogeneous conductive material, or considering the carbon foam as an analogue of photonic crystal with dielectric losses.

The EM properties of carbon foams can be controlled mainly through their density (or porosity) and the nature of the constituting carbon. The cell size, which is small compared to the wavelength in the microwave domain, does not seem to have any noticeable effect according to [12], but because density and cell size were always correlated with each other so far, this finding should be confirmed. The EM properties of carbon foams can also be further improved by other methods such as filling the cells with CNTs – polymer composite [15] or by impregnation/deposition of magnetic or dielectric nanoparticles on the surface of the cells [22]. Finally, it should be noticed that carbon foams are already used in applications such as high-temperature insulation for aerospace vehicles where EMI shielding is also of great interest [16].

Thus, so far, the influences of bulk density, cell size and connectivity on the EM properties of carbon foams have never been investigated separately. The present work is thus devoted to the analysis of the EM properties of CVC and RVC foams, presenting various structures especially in terms of bulk densities and cells sizes. For that purpose, the evolution of the properties of those foams was analysed over the broadest frequency range ever investigated: from quasi-static (20 Hz) to microwave, terahertz and near-infrared frequencies.

2. Materials and methods

2.1. Materials

As explained in the introduction, the CVC foams investigated here were thoroughly described in a previous paper in terms of synthesis protocol, average cell size, bulk density and vitreous carbon texture [1]. All CVC foams were prepared by carbonisation at 900 °C of phenolic-furanic rigid foams whose formulations, detailed in Ref. [1], were called STD, PEG, TRITON, PLURO, PMDI, T1, T2, T3P, T3DE, T4, TW, PPPT and SF. The bulk densities and the cell sizes of these new materials could be tuned by using various amounts of blowing agent in the formulation of the organic precursor foams. As a result, samples presenting either different cell sizes for a same average bulk density, or a same average cell size for different bulk densities, were successfully produced.

One formulation called RT, however, led to carbon foams whose porous structure is only based on struts, i.e., without cell walls (see again Fig. 2). Since the carbon source was again phenolic-furanic resin, and because this material was pyrolysed at the same temperature of 900 °C as before, it is a reticulated vitreous carbon (RVC) foam. In addition, other RVC foams were also prepared from polyurethane foams used as templates, by hydrothermal impregnation of resorcinol-formaldehyde resin followed by carbonisation as described in Ref. [2]. The foams prepared from templates having 30 to 80 pores per inch were called TRF and had very similar bulk densities ranging from 0.029 to 0.035 g cm^{-3} but cells of average diameters ranging from 2070 to 738 μm, respectively. In the present study, RVC foams were also prepared with the same templates but impregnated with a resin derived from furfuryl alcohol in order to

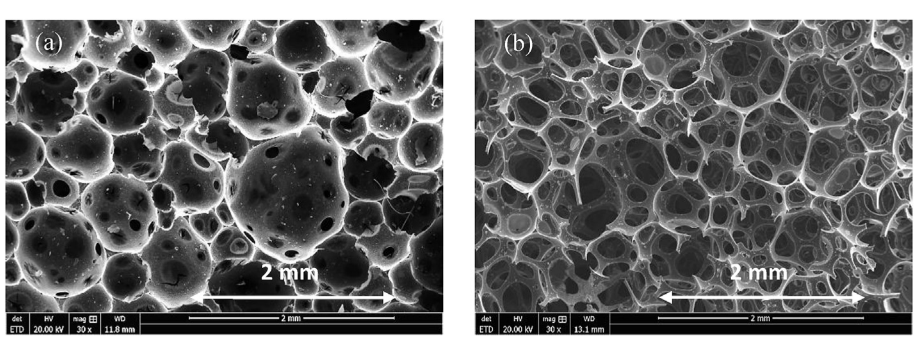

Fig. 2. Typical SEM pictures of: (a) CVC foam (formulation PPPT; density 0.094 g cm^{-3}), and (b) RVC foam (formulation RT, density 0.043 g cm^{-3}).