FROM MICROSTRUCTURE TO ACOUSTIC BEHAVIOUR OF POROUS MATERIALS

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1. INTRODUCTION

Subject. To study how the microstructure (form and structure revealed using microscopy) of a foam can be used to determine its general sound absorption properties.

Background. (i) Foams can be seen as an arrangement of cells paving space [1], whose form and constitutive struts are determined by physical principles [2]. The two-dimensional ordered monodisperse foam is the celebrated honeycomb structure, the hexagonal structure. Kelvin's tetrakaidecahedron packed in a bcc structure is an acceptable equilibrum structure. (ii) The exact acoustic response of a microstructural system is restricted to the case of tubes of constant cross-section and slits. A real porous material is consequently seen as equivalent-fluid medium, of effective complex and frequency dependant density $\widetilde{\rho}$ and bulk modulus $\widetilde{K}$ (or equivalent set of dissipative functions) under the assumption of a rigid frame. Hence, a macroscopic Helmoltz equation provides a suitable paradigm for acoustic propagation and dissipation through porous media [3]. However, local geometrical variables (for example radius and thickness of tubes) do not appear explicitly in such a macroscopic description.

Purpose. To describe a novel procedure to characterize the sound absorption of reticulated foams (i.e. with open cells) from their microstructure.

Relevance. The enhancement of sound absorption properties of porous materials relies on the capacity to describe (i) microstructure and (ii) microstructure – acoustic energy interactions.

Outline. In Sec. II, methods to compute effective acoustic properties of reticulated foams are presented. Simulation results for effective acoustic properties of scaled cellular systems (Kelvin or honeycomb structure) are given in Sec. III and compared with direct experimental measurements.

2. METHOD

In this approach, one defines an elementary cell paving periodically space, experimentally identified or scaled by a simple geometrical model. We will develop here some of the essential notations relating to structure. Dissipation functions are computed by sophisticated numerical methods from the microstructure.

2.1 Input parameters, some necessary definitions

At microscale. Foam structure is experimentally identified by computed microtomography (μCT), including the average: (i) topology of a three-dimensional unit cell paving periodically space, (ii) shape of the struts of length ℓ and thickness t.

At macroscale. Porosity Φ and thermal characteristic length Λ' can be determined by independent and non-acoustical techniques. The porosity is actually the more common macroscopic parameter and is confidently measured. It is defined by the pore volume to bulk volume ratio (fluid volume fraction). The quantity Λ' is also known as the hydraulic radius and defined by twice the pore volume to pore surface ratio, or $2V_p/S$.

2.2 Cellular model, linking micro to macro scale

Once the morphology has been identified, a micro-macro relationship can also be established, leading to a cellular model of the foam. For example, in the case of (i) the Kelvin structure (a tetrakaidecahedron unit-cell or semi-regular polyhedron of fourteen sides paving efficiently space), (ii) having struts of regular triangle cross-section shape, the macroscopic indicators Φ and Λ' are written according to the microstructural indicators ℓ and t.

Therefore, these expressions for Φ and Λ' determine macroscopic surface and volume information for the Kelvin structure. For the purposes of our study, the solutions of this system are of primary interest as they describe the local dimensions of reticulated foams when microstructural information is not available.

2.3 Local computation of the dissipation functions

The result relating the porosity Φ and the thermal characteristic length Λ' to the sizes of the triangular struts arranged in a Kelvin structure, ℓ and t, allows for a simple cellular model to solve the viscous and thermal problems.

Viscous problem. It has been shown that the Finite Element Method leads to a velocity field that is a solution of the Navier-Stokes equation [4]. Periodic boundary conditions are easily implemented under the Femlab® environment. The relevant physical properties are ensemble averages.

Thermal problem. The first passage sphere algorithm [5] was used to determine the frequency dependent bulk modulus of air saturating different arrangements of parallel solid cylinders [6]. We shall apply this algorithm to more complex three dimensional geometries, such as media comprised of Kelvin cells.

3. RESULTS

As a result, the dynamic bulk modulus can be computed in a periodic unit cell as shown in figure 1 and 2, as well as the macroscopic parameters (table 1).

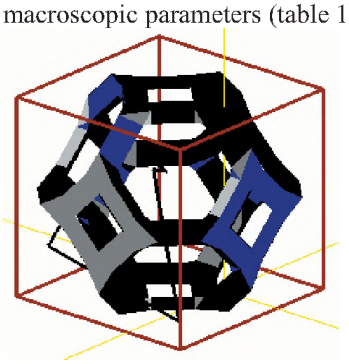

Fig. 1. The Kelvin structure paves periodically space. A "random walker" is seen. It serves to compute an essential thermal dissipation function, the dynamic bulk modulus.

In Tab. 1, the computed viscous macroscopic parameters are compared with measurements. The numerical resistivity σ is greater than the experimental one. In the hexagonal model, struts perpendicular to the flow direction increase resistivity.

In Fig. 2, the computed dynamic bulk modulus $\widetilde{K}$ is compared with measurements. Here, it is seen that there is a shift in amplitude for the polymeric foam. Therefore, the zero acoustic temperature boundary condition is not valid for this material. As shown by Tarnow in 1995, it is due to the fact that the ratio of the air/solid heat capacity coefficients is not small.

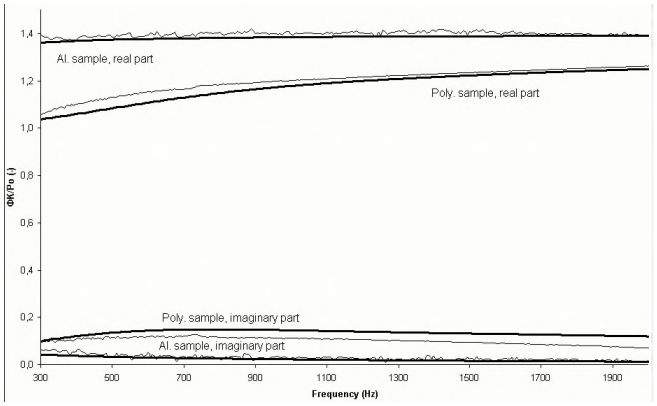

Fig. 2. Bulk modulus as a function of frequency for two real samples. Computed by Brownian motion simulations and compared to measurements for (i) identified (Duocel® al. foam 40 ppi) and (ii) scalded (polymeric foam) Kelvin structures. Top: real parts. Bottom: Imaginary parts.

Table 1. Macroscopic viscous properties

	porosity Φ (-)	thermal length Λ' (μm)	resistivity σ ($N.s.m^{-4}$)	tortuosity α_∞(-)	viscous length Λ (μm)
Measure	0.921 +/- 0.001	1926 +/- 431	177 +/- 21	1.07 +/- 0.01	988 +/- 57
Finite Element Method	0.911	1910	339	1.04	1047

4. CONCLUSION

We have proposed a method to determine the macroscopic parameters of absorbent materials from the knowledge of their cellular microstructure, either identified by μCT, or scaled by a macro-micro geometrical model. A good agreement is found between the microstructural approach and classical macroscopic measurements for the two samples studied. The principal contribution of the present work is that all the relevant quantities have been computed on cellular systems (Kelvin or honeycomb structure). In summary then, we have computed, for 3D cellular porous systems, the dynamic thermal permeability k', its static value k'_0, the static thermal tortuosity α'_0 , the transition frequency f_{tc} and the form factor M'. Study of the fluid velocity field for a hexagonal porous system (2D counterpart of the Kelvin structure) revealed significant quantitative agreement between macroscopic parameters derived and measured from real aluminium foam. This lends support to the idea that there is a deep connection between Kelvin structure and real reticulated foams: the scaled Kelvin structure is a representative configuration of reticulated foams.

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ACKNOWLEDGEMENTS

This work was supported by NSERC Canada and FQRNT Québec.

C. Perrot would like to thank R. Bouchard, F. Gauthier, E. Gautier, I. Jovet and M. Lefebvre for assistance; Alcan, CQRDA, and Région Rhône-Alpes for financial support.