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► **To cite this version:**

Elio Di Giulio, Camille Perrot, Raffaele Dragonetti. Towards a control of acoustic energy conversion in structured porous materials. Symposium on the Acoustics of Poro-Elastic Materials (SAPEM'23), Nov 2023, Sorrento (Naples), Italy. hal-04393707

HAL Id: hal-04393707

<https://hal.science/hal-04393707>

Submitted on 15 Jan 2024

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Towards a control of acoustic energy conversion in structured porous materials

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1 Introduction

Manipulating porous material's geometry allows the control of internal viscous and thermal processes. Generally, these processes are interconnected due to the material's microstructure. For instance, simple geometries like uniform cross-section materials exhibit interrelated viscous and thermal reactions. By altering the pore size (i.e. the hydraulic radius), both thermal and viscous effects can be tuned. This applies to conventional acoustic materials such as fibers, open-cell foams, and granular materials. However, there are cases where independent management of thermal or viscous effects is crucial. In thermoacoustics, enhancing heat exchange while minimizing viscous losses is necessary. In acoustics, maximizing both effects is essential for dissipating acoustic energy. Nevertheless, there are situations, like low particle velocity scenarios (e.g., thin materials on rigid surfaces or in low-frequency cavities), where increasing viscous dissipation may not be impactful. For this reason maximizing the thermal power exchanged could improve acoustic absorption. In this work we will show some preliminary studies conducted on a particular geometry of porous material in which it is possible to control these two effects separately

2 Theoretical formulation

The variation of the sound power \dot{E} in a channel of infinitesimal length dx , can be expressed as [1, 2, 3]

$$\frac{d\dot{E}}{dx} = \frac{1}{2} \Re \left[\tilde{U} \frac{dp}{dx} + \tilde{p} \frac{dU}{dx} \right], \quad (1)$$

where p and U represent the acoustic pressure and volume velocity fields. \Re and \sim indicate respectively the real part of the complex number and the complex conjugate. By combining the Eq. (1) with the solution of momentum and energy equations, one obtains

$$\frac{dE}{dx} = -\frac{1}{2} \frac{i\omega A}{\gamma p_m} \theta_\kappa |p|^2 - \frac{1}{2} \frac{i\omega \rho_m}{A} \theta_\nu |U|^2 + \frac{1}{2} \Re [g\tilde{p}U]. \quad (2)$$

Here, ω is the angular frequency, ρ_m, p_m, γ are respectively the static density, pressure and the specific heat ratio. A is the cross-sectional passage area of the fluid. The term g is function both of the microstructure and the thermal gradient dT_m/dx across the porous material. It is fundamental in the formulation of the thermoacoustic phenomena. θ_ν and θ_κ are respectively some viscous and thermal loss functions. They allow taking into account the dissipated energy occurring from viscous and thermal mechanisms. They strictly depend on the microgeometry and can be expressed as depending on the *thermoviscous* functions f_ν and f_κ , as follows

$$\theta_\nu = \frac{\Im [-f_\nu]}{|1 - f_\nu|^2}, \quad (3)$$

$$\theta_\kappa = \Im [-f_\kappa]. \quad (4)$$

3 Materials and methods

The dynamic frequency dependent responses of a porous material rely on several *transport parameters*, namely porosity, tortuosity, viscous and thermal characteristic lengths, and static viscous and thermal permeabilities. Nevertheless, all these parameters are correlated to the microgeometry of the material

and their values can not be independently tuned. This leads to an interdependent viscous and thermal response in terms of f_ν and f_κ , as well as θ_ν and θ_κ . Here, we show a particular unit cell exhibit the property to regulate the viscous and thermal behaviour almost independently. It has been highlighted how the viscous behaviour is closely tied to the throat section area inside the microgeometry, while the thermal behaviour depends on the volume to surface ratio. The identified microstructure is a tetrakaidecahedron referred as a Kelvin cell-based geometry, optimized to accommodate manufacturing constraints, and characterized by walls with precise opening ratios and thickness (Fig. 1).

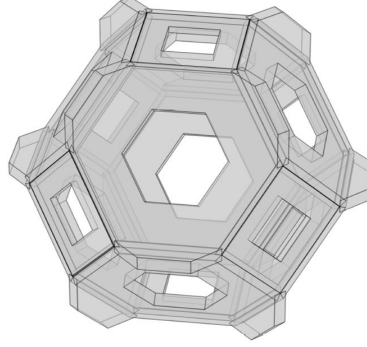


Figure 1: Selected unit cell which can be used to control viscous and thermal dissipation mechanisms.

4 Results and conclusions

Fig. 2 displays the results obtained from numerical simulations in terms of θ_ν and θ_κ versus the frequency axis. It can be highlighted how the variation of a single geometrical parameter, such as the membrane opening ratio, has strong influence of the viscous behaviour with low effect on the thermal part. On the other hand, the variation of the wall thickness influences the thermal behaviour without changing the viscous response. In conclusion, the presented geometry could open a way on the research on this kind of materials. In fact, based on the application, it could be required to maximize the viscous behaviour over the thermal one and *vice versa*.

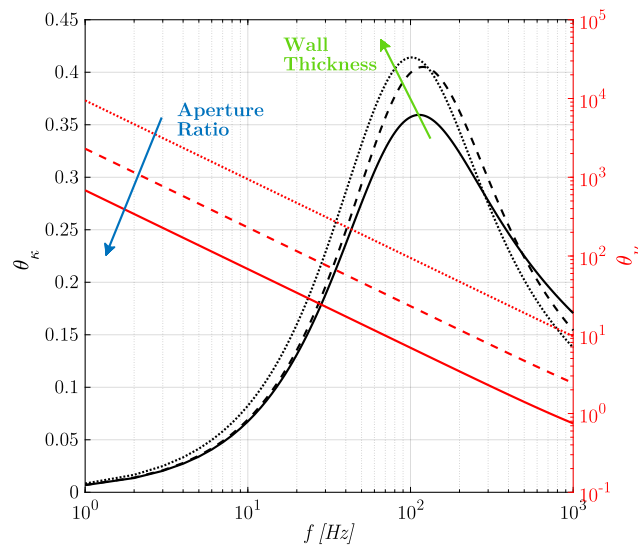


Figure 2: Illustration of the evolution of the viscous θ_ν and thermal θ_κ relaxation functions as a function of frequency for varying aperture ratio and wall thickness.

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