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Acoustic absorption of solid foams with thin membranes

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We measured the acoustic absorption, in the 0.5–6 kHz frequency range, of polyurethane foams with mean pore diameters between 0.6 and 3.2 mm. Two types of foams were investigated: classical open-cell ones versus membrane foams, in which thin polyurethane membranes were preserved during solidification. Interestingly, the latter presented better absorption abilities, indicating that membranes could be an asset for sound absorption. *Published by AIP Publishing.*
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Noise pollution has become a major problem in our modern life. Industrial and academic research has continuously tried to design more efficient soundproofing materials. Recently, exotic structures have been considered, using the concept of double-porosity[1,2] or introducing low frequency resonators to enhance the dissipation.[3–5] Traditionally, sound absorbers have been porous media, such as mineral wools or foams. A first general rule for their efficiency is that no obstacle should prevent the sound from propagating in the medium; otherwise, the acoustic energy is reflected back instead of being absorbed. For foams, for example, it means that open-cell structures are preferred. On the other hand, the physical picture is that when sound penetrates such a medium, it loses a lot of energy because of the large surface area it can interact with. As a rule of thumb, one finds that good absorption is obtained when the typical pore size corresponds to the heat and viscous diffusive length in air, which is of the order of 50 μm at 2 kHz, for example. Hence, open-cell porous materials with pores sizes of tens of micrometers are good candidates for efficient sound absorption and are therefore used extensively for sound insulation.[6,7] In this letter, we show that there are exceptions to these established rules: closed-cell foams with millimeter-sized pores can actually be good sound absorbers.

The foams we studied were provided by the company FoamPartner. They were made of polyurethane, with a porosity (air volume fraction) of 98%. Their most interesting feature, for us, was that most of the membranes which separate neighbouring pores (Fig. 1) were preserved during solidification.[8] As these membranes are not desired for most of the applications, the manufacturer employs a technique by which the membranes are removed through a hydrogen explosion. We thus obtained solid foam samples from the same production batch with the same chemical composition and structure, except for the presence of membranes. Figure 1 shows close-up views of one open-cell foam (top) and its closed-cell equivalent (bottom), where membranes are clearly visible. We obtained the mean pore size by image analysis, using the number of cells along a line. The foam density was obtained by weighting a well-defined foam volume, thus giving us access to the foam porosity (assuming a 1200 kg/m^3 density of polyurethane). The thickness of the membranes was measured by white light spectroscopy (Ocean Optics) at different locations of the sample taking 1.6 for the optical index of

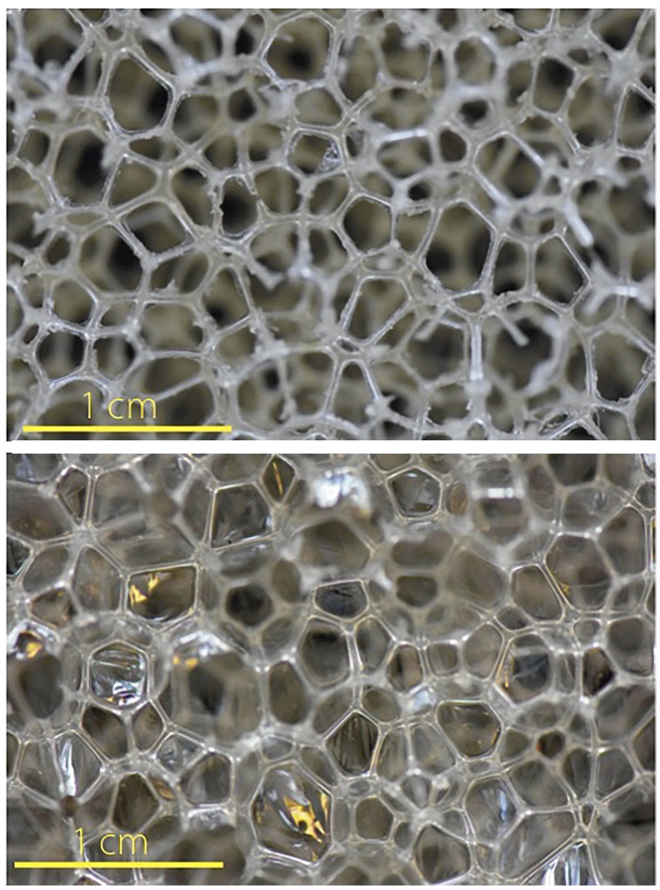

FIG. 1. Comparison of an open-cell foam (O1, top part) and a closed-cell one (C1, bottom part). Both have very similar porosity and mean pore sizes, but C1 has membranes whereas O1 has not.

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TABLE I. Characteristic parameters for four foam samples. Letters O and C refer to open and closed-cell foams, respectively. Samples 1 were with large pores, whereas samples 2 had smaller pores.

Name	Mean pore diameter (mm)	Density (kg/m^3)	Porosity Φ (%)	Membrane thickness (μm)
O1	3.2	23 ± 1	98	No membrane
C1	3.2	25 ± 1	98	5 ± 0.9
O2	0.6	32 ± 1	97	No membrane
C2	0.6	32 ± 1	97	1.7 ± 0.4

polyurethane.[9] All these characteristic parameters of the samples are summarised in Table I.

Acoustic properties were measured using an impedance tube working between 0.5 and 6 kHz and are schematised in Fig. 2. We first investigated the absorption coefficient: $\alpha = 1 - |r|^2$, where r is the reflection coefficient. Figure 3 shows the absorption coefficients for 2 cm-thick samples of the four foams listed in Table I. For each type of foam, two samples were measured (open and solid symbols in Fig. 3) to check the reproducibility of our measurements. Quite surprisingly, the membrane foams were found to be much more attenuating than their open-cell equivalents. Foams C1, for instance, reach a quasi-perfect absorption for frequencies larger than 2 kHz, while O1 samples hardly absorb 10% of the energy at 5 kHz. It means that, contrary to the rule exposed earlier, the solid membranes do not seem to act as solid obstacles in this case.

For the open-cell foams O1 and O2, the results are well described by the Johnson-Champoux-Allard-Lafarge (JCAL) model (black lines in Fig. 3), which has been developed to describe the visco-inertial and thermal dissipative effects inside a porous medium with connected open cells.[10–12] This model needs six parameters: the porosity Φ, the static air flow resistance σ, the high frequency tortuosity α_∞, the characteristic lengths of the structure regarding viscous (Λ) and thermal phenomena (Λ'), and the static thermal permeability k'_0. The porosity Φ was known (Table I), and the five remaining parameters were obtained following the method described by Panneton and Olny.[13,14] The results are shown in Table II. Similar tortuosities were found for both samples, and σ was higher for O2, the foam with smaller pores. For the membrane foams, not surprisingly, the method led to non-physical parameters, meaning that important mechanisms are not taken into account by the JCAL model.

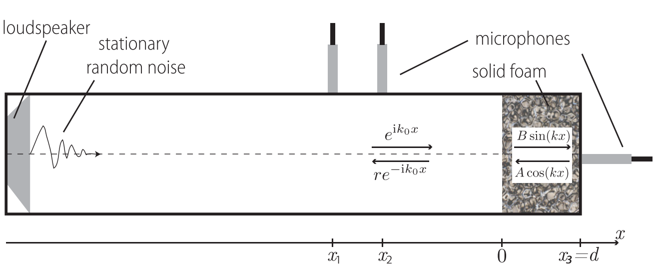

FIG. 2. Impedance tube mounted with two microphones in reflection and one in transmission. Characteristic parameters of the tube: $x_1 = -14.5$ cm, $x_2 = -12.5$ cm, $x_3 = +2$ cm (or $+1$ cm), and the diameter of the tube was 29 mm.

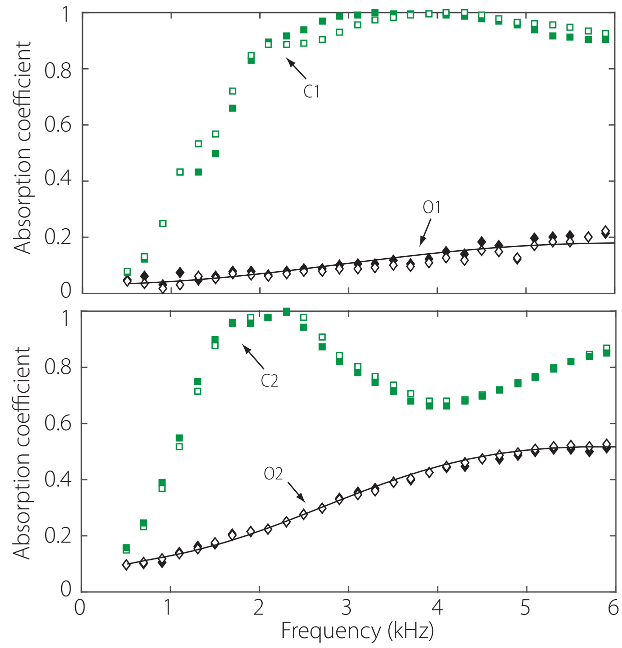

FIG. 3. Measured absorption versus frequency for open cell foams (O1 and O2, black symbols) and closed-cell foams (C1 and C2, green symbols). Samples were 2 cm thick. Reproducibility was tested by measuring 2 samples of each type (solid and open symbols). Solid black lines show JCAL model for the open-cell foams.

To gain further insight into the acoustical difference between the two types of foams, we measured their effective density and longitudinal modulus, using the 3-microphone technique[15,16] (see setup in Fig. 2). Figure 4 shows the real and imaginary parts of the effective longitudinal modulus and density measured on O2 and C2 samples, as functions of frequency. Similar results were obtained with O1 and C1 samples. Let us first focus on the results for the open-cell foam O2 (diamonds in Fig. 4). The longitudinal modulus is found to be close to 140 kPa, the value of the adiabatic modulus for pure air. It means that sound propagation is adiabatic in this frequency range, which is consistent with the fact that pores here are much larger than the thermal diffusive length. For the same reason, the effective density is found to be close to the value in pure air ($\sim$1.5 kg/m^3, versus 1.2 kg/m^3 for air). If we now turn to the results for the membrane foam C2 (squares), we see that, at the low frequency limit at least, the measured effective longitudinal modulus is very similar to the open foam case. The situation is totally different for the effective density: it is of the order of 8 kg/m^3 at 1 kHz, more than 5 times higher than for the open-cell foam. This is a striking result because membranes in C2 represent a negligible addition of matter compared to O2 (it does not change the weight of the sample). Note that the imaginary part of the effective density is also strongly increased by the

TABLE II. Values of the JCAL parameters obtained for the open cell foams O1 and O2.

Name	Φ	α_∞	σ (Pa s/m^2)	Λ (mm)	Λ' (mm)	k'_0 (μm^2)
O1	0.98	1.04	1100	1.06	2.08	5.42
O2	0.97	1.01	2200	0.23	0.66	1.42

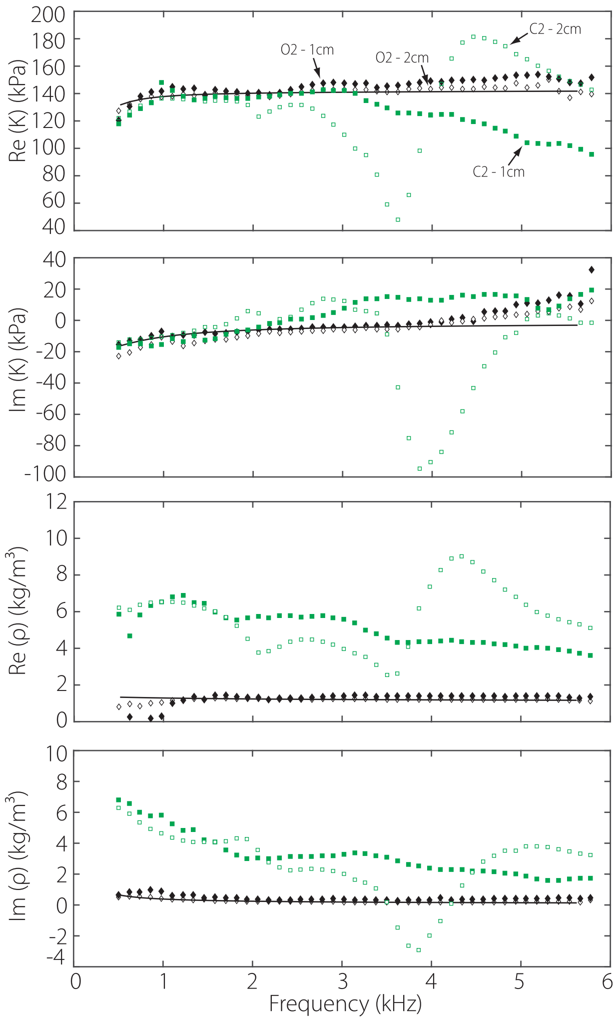

FIG. 4. Effective acoustic longitudinal modulus K and density ρ as functions of frequency for the small pore foams. The results for open-cell foams are shown in black symbols, while those for closed-cell ones are in green. Two thicknesses are shown: 2 cm (open symbols) and 1 cm (solid symbols). Solid black lines show the JCAL model for the open-cell foam O2.

presence of membranes, which explains the high level of absorption obtained with these samples.

At higher frequencies, one can remark that the measured effective longitudinal modulus and density fluctuate a lot for the 2 cm C2 sample, with marked dips around 4 kHz. We interpret this phenomenon as a sign of a resonance of the solid phase, due to a coupling between the fluid and solid displacements.[17,18] As the frequency of this resonance is expected to be inversely proportional to the thickness of the sample, we used a thinner sample of the same foam to test our interpretation. As shown by the solid squares in Fig. 4, the effective longitudinal modulus and density measured on a 1 cm-thick sample show a smoother behavior, consistent with a resonance that would have been shifted beyond 6 kHz. Note that for the O2, no difference was obtained between the 1 and the 2 cm-thick samples.

To complete our study, we also measured the acoustic properties of foams with intermediate pore sizes. Figure 5 proposes a summary of our effective density measurements for open and membrane foams with different pore sizes (0.6, 0.85, 1, 1.7, and 3.2 mm). All the samples had the same porosity and mass density. We took the average values of the

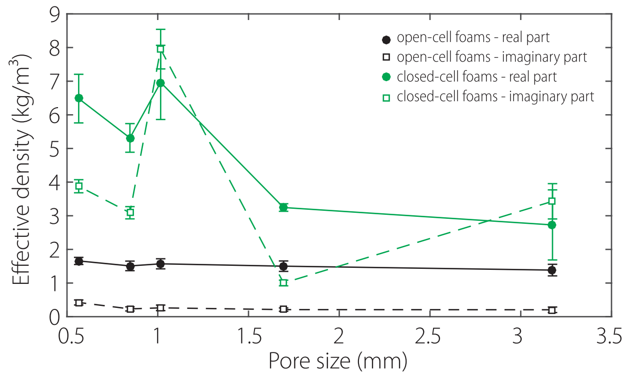

FIG. 5. Real and imaginary parts of the effective density, evaluated on the 2.5–3.5 kHz interval, for foams with different pore sizes.

real and imaginary parts of the effective density over the 2.5–3.5 kHz interval (with 1 cm-thick samples for membrane foams), and we indicate with errorbars the amount of variations on this interval. For open-cell foams, both the real and imaginary parts of the effective density decrease with the pore size. For membrane foams, the tendency is not as clear. We also investigated the role of the mean membrane thickness, but no clear tendency was apparent either. The main conclusion we draw from Fig. 5 is that both the real and imaginary parts of the effective density are always larger when foams have membranes. It suggests that the abnormally high absorption reported in Fig. 3 would come from an additional viscous dissipation mechanism brought by the membranes.

It is interesting to note that, despite the large number of studies on acoustical devices with membranes, there is no model available that can be applied to the solid thin-membrane foams studied in this letter. One can roughly distinguish two classes of models, coming either from the poro-acoustics community or from the acoustic metamaterials one. In the first class of models, acoustic predictions have been made using a fairly detailed description of the complex structure of the foam.[24] Yet, the membranes were considered as solid and non-deformable.[23] In the second class of models, on the other hand, the dynamics of the membranes has been considered but the structures are much simpler, with one- or two-dimensional geometries.[25–27] A complete model is therefore still needed. A promising direction is the recent work by Venegas and Boutin[22] on permeo-elastic materials. Another direction is inspired by recent work on liquid foams, which are constitutively with cells closed by thin membranes. Liquid foams have proven to be efficient for mitigation of sound and blast waves.[19,20] They have also been found to present a low frequency resonance, due to the thin membranes, for which a model was proposed.[21] However, adapting the model to solid foams is not straightforward.

In summary, the results reported in this letter suggest that not only open-cell materials can be effective sound absorbers. When the cells are closed by membranes that are sufficiently thin not to behave like acoustic reflectors (in practice, a few micrometers for audible frequencies), good performance can be obtained with closed-cell foams, calling for the development of research on thin-membrane foams.

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