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Open-cell poly(vinylidene fluoride) foams with polar phase for enhanced airborne sound absorption

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Open-cell foams of polyvinylidene fluoride (PVDF) homopolymer were fabricated with the content of polar phase being changed by thermal treatment, and their airborne acoustic absorption performance properties were measured comparably in an acoustic tube. The experimental results showed that the sample with the more polar phase and hence a stronger local piezoelectric effect exhibited a significantly larger acoustic absorption coefficient. In addition to the conventional visco-inertial, thermal and materials damping effects, our analysis indicated that the thin and polar struts of PVDF foams with the polar phase and the local piezoelectric effect may further enhance the mechanical damping by converting the excited mechanical vibration to electricity through the local piezoelectric effect and increasing the friction and viscous loss at the fluid-solid interface in the presence of electrical charges. The open-cell polymer foams with high content of the polar phase and the local piezoelectric effect have great potential for passive airborne noise mitigation applications. *Published by AIP Publishing.* <https://doi.org/10.1063/1.5048336>

Acoustic absorption became a subject of importance for both noise mitigation and interior acoustic optimization because of the strong revival in advanced technologies that led to increasing noise level tremendously. Among the various environmental issues, noise pollution has been growing over the past years, especially in many developed urban areas. Active, passive, and hybrid noise mitigations are the commonly used approaches for noise cancellation.^{1,2} Passive noise absorption technique is attractive in most of the applications because it does not require an external source of electrical energy nor a complex algorithm for gaining control over such a complicated system.² The dissipation of sound in the audible range transmitting medium, such as air, is quite minimal and consequently, the noise mitigation approaches had emerged starting with W. C. Sabine around 1895 when he studied for the first time the relationship between reverberation in a room and its sound absorption.³ The passive noise approach realizes the efficient absorption of sound using absorbing materials. The performance of such materials depends on their microstructure in which the sound energy is dissipated over several mechanisms associated with the solid phase, the fluid phase, and the solid-fluid interface.⁴ Ultimately, all acoustic energy is converted into random thermal energy, and this is the typical case of sound energy dissipation.⁵

Sound wave energy is dissipated through three types of interactions: visco-inertial, thermal, and structural mechanisms.^{6–8} The visco-inertial dissipation mechanism occurs in the region of the solid surface, where the non-slip boundary

condition can take place and cause a large relative motion within the viscous boundary layer, which is the first mechanism for sound energy dissipation.^{6,7,9} Thermal dissipation mechanism is another mechanism, which occurs by the heat conduction through the solid phase resulting in the breakdown of the adiabatic character of sound propagation.¹⁰ Furthermore, structural dissipation mechanisms are associated with the structural damping effect that takes place due to the excitation of a solid structure when it is struck by a sound wave.^{11–13} It follows that materials with a large microstructure fluid-solid interfacial area, as in porous media, usually leads to substantial dissipation coefficients, because such type of material allows efficient energy exchange between the fluid- and solid-phases.^{14,15} Sound absorbing materials are classified based on their microscopic structure into cellular, fibrous, and granular.^{16,17} They can also be classified into two classes, open- and closed-pores, based upon the macroscopic configurations of the absorbing materials. Open pores, which have interconnected and continuous channels, are connected to the ambient environment, while closed pores are those pores that are isolated from their neighbors.^{8,11} The open-cell porous materials, which have two phases comprising a solid framework intertwined with a network of pores with many interfaces for the interactions, are desirable as superior sound absorbing materials.

Absorption of acoustic energy depends on the sound wave frequency that is governed by the linear-response law because sound is associated with very small air displacement velocities.^{14,17} The linear response law dictates both the frictional forces and fluxes to be linearly proportional to the rate of dissipation;^{18,19} thus, the absorption rate of low-frequency sound is small. Intrinsically, almost all materials have a

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weak absorption of the sound energy, particularly below 2 kHz. Due to the limitations of porous materials at low frequency, other complicated methods have been evolved to overcome this problem, including the use of acoustic meta-materials^{20,21} and sonic crystals.²² As a result, conventional sound absorbing materials possess fixed absorption spectra which can only be modified by changing the sample thickness that must be within a quarter of the sound-wavelength or through inventing a new approach for enhancing the low-frequency sound absorption performance.^{2,14}

The use of piezoelectric materials for noise control technologies passed by enormous advancements. Lead zirconate titanate (PZT) piezoelectric ceramics have been utilized as films for suppression of the mechanical vibration plates by Yang and Chiu,²³ beams by Blanguernon *et al.*,²⁴ and shell structures by Balamurugan and Narayanan.²⁵ Moreover, structural vibration damping technologies have been employed utilizing the piezoelectric effect such as in the piezoelectric shunt damping and piezoelectric damping composites.²⁶ A smart foam consisting of a passive layer bonded to one surface of an active piezoelectric composite while the other surface being bonded to the vibrating plate surface was proposed to achieve a broad frequency range of vibration and acoustic noise control.²⁷ Rahimabady *et al.* first introduced the concept of hybrid local-piezoelectric and electrical conductive functions to achieve high-performance low-frequency airborne sound absorption, by using complex composite foams made of porous polar polyvinylidene fluoride (PVDF) mixed with conductive single-walled carbon nanotubes (SWCNTs).²⁸ But, after all these efforts, a profound understanding on how the introduction of piezoelectric activity into acoustical foams works and what associated complications could take place is not achieved yet. Hence, in this work, open-cell foams of simplified PVDF homopolymer composition with and without piezoelectric effects, were produced and used comparably for airborne noise mitigation investigation. How the polar phase and the local piezoelectric effect would contribute to the air-borne sound absorption was addressed.

Experimental details of foam preparation and characterization are presented in the [supplementary material](#).

It is well known that sound absorption is related to various materials properties. To assess the effect of local piezoelectric activity on the sound absorption performance, open-cell porous PVDF foams identical in all aspects except for their polar phase content are required. In this work, open-cell PVDF homopolymer foams prepared under the same conditions using a sugar templating method with the mass ratio of PVDF:sugar = 1:9 were examined before and after thermal annealing at 140 °C for 2 h. Attenuated total reflection infrared (ATR-FTIR) spectroscopy technique was used to study the polar phases in the PVDF foams. Figure 1 shows the ATR-FTIR spectra of the obtained PVDF foams. The characteristic vibration bands designated to the polar β -phase are at 840 cm⁻¹ (CH₂ rocking and CF₂ asymmetrical stretching) and 1279 cm⁻¹ (C-F stretching vibration), while in contrast, the characteristic bands associated with the non-polar β -phase are at 766 cm⁻¹ (CH₂ in-plane or rocking) and 976 cm⁻¹ (CH₂ twisting).^{24,25} As shown in Fig. 1, both β - and α -phases exist in the open-cell PVDF foams, while

FIG. 1. The ATR-FTIR spectra of porous PVDF foams before and after thermal annealing. The unmarked peaks are common for both β - and α -phases.

the polar β -phase is significantly enhanced after the thermal annealing. Thus, the annealed PVDF foam with higher polar β -phase content should possess a stronger local piezoelectric effect than the unannealed foam. Furthermore, the FTIR spectra show apparent overall crystallinity enhancement besides the increase of β -phase content in the annealed foam.

Figures S1(a, b) and S1(c, d) show the morphology and the respective pore size histogram of the PVDF foams before and after thermal annealing. The PVDF foams are highly porous with open cell configuration, with the pore size for both samples around 500 μ m and below. The micrographs and the pore size distribution histogram reveal that the thermal annealing process does not substantially affect the morphology including the pore size distribution of the PVDF foam. The porosity of the PVDF foam was estimated using solvent saturation method.^{29,31} In this method, a dry sample is immersed in a solvent, usually water or alcohol, and the change in the original weight is monitored until a constant weight is achieved. Then, the porosity is calculated using the following equation:

$$\phi(\%) = \left(\frac{(m_{\text{sat}} - m_d)/\rho_{\text{solvent}}}{V_a} \right), \quad (1)$$

where m_{sat} is the weight of the sample saturated with solvent, m_d is the dry weight, ρ_{solvent} is the density of the used solvent, and V_a is the apparent volume. The porosity was adjusted by controlling the mass ratio of PVDF and sugar to be approximately 90% in the prepared foam.

Stiffness is an important mechanical parameter affecting the sound absorbing properties.^{30,31} To assess its effect, the dynamic stiffness of open-cell PVDF foams was evaluated using dynamic mechanical analysis (DMA). The dynamic stiffness measurements of the prepared foams before and after thermal annealing are shown in Fig. S2, where no significant change is observed for the open-cell PVDF foams after the thermal treatment.

Figure 2 presents the sound absorption coefficient in the frequency range of 500–6400 Hz of PVDF foams with a thickness of 10 mm before and after thermal annealing. The sound absorption coefficient shows a significant increase after the thermal annealing of the PVDF foams at 140 °C for 2 h, while the microstructure and the mechanical properties

are maintained after annealing as shown in Figs. S1 and S2, respectively. This improvement in sound absorption performance may be attributed to the increase of the polar β -phase content with the local piezoelectric effect in the PVDF foams due to the thermal annealing treatment as shown in Fig. 1. We further measured the electrical resistivity of the open-cell PVDF foams as shown in Fig. S3 and found a valley around 3.7 kHz, which is very close to the maximum damping peak in the acoustic absorption coefficient measurement as shown in Fig. 2. This observation is consistent with the result of how the variation of the external resistive load affects the damping factor in the conventional piezoelectric shunt damping.³² Thus, the local piezoelectric effect in combination with appropriate matching electrical resistivity in the open-cell PVDF foams can further enhance the acoustic absorption.

After annealing, the change in the crystalline phases of PVDF must affect the polarization and the dielectric property of PVDF foams.³⁰ As shown in Fig. 3, both the dielectric constant and the dielectric loss of the PVDF foams increased after the thermal annealing, which could be an indication of the enhancement in the polar phase and polarization. The enhanced polar β -phase and local polarization should improve the piezoelectric response, but it is not straightforward to clarify their relationship because of the challenge in measuring the local piezoelectric effect, particularly in the highly soft and porous foam samples. It should be noted that the open-cell PVDF foams have significantly lower dielectric constant than the solid PVDF counterpart due to the extremely porous structure.³³

To investigate the ability of both annealed and unannealed samples in converting the sound mechanical energy into electrical output energy, a homemade measuring setup was constructed to conduct the experimental measurement for both the annealed and unannealed foams after electrically poled using corona discharges under 60 kV for 3 mm-thick samples. Figure S4 shows the setup used for measuring the output voltage response at different sound pressure levels. A loudspeaker of an acoustic impedance tube was used in these measurements as a sound source on one side of the tube,

FIG. 2. The sound absorption coefficient of PVDF foams before and after thermal annealing.

FIG. 3. Dielectric constant and dielectric loss of PVDF foams at room temperature before and after thermal annealing.

while a microphone was used to measure the sound pressure level (SPL) closely to the sample on the other side of the tube. The electrodes on the samples made of silver paste were collected to oscilloscope through a low noise amplifier (1:1) to collect the generated electrical charges.

Figure 4 presents the output voltage versus various sound pressure levels (SPLs) at 700 Hz for both annealed and unannealed open-cell PVDF foams before and after electrical poling. Although both annealed and unannealed samples did not exhibit any substantial piezoelectric voltage response, they did show a substantial difference in the output voltage after poling. The annealed PVDF foams showed larger piezoelectric output, which could be attributed to the enhancement of the polar β -phase due to the thermal annealing (as shown in Fig. 1) and the poling-induced polarization orientation. Without the polarization orientation, local polarization from the existence of the β -phase and local piezoelectric response should also exist although they could not constructively generate a substantial observable overall output voltage due to the random polarization orientation. Nevertheless, even before poling, the annealed PVDF foam exhibited significantly improved noise absorption performance than the unannealed sample, indicating that the content of the polar β -phase and the local piezoelectric effect instead of the overall piezoelectric effect may have played a more critical role in noise absorption.

FIG. 4. Voltage output at different sound pressure levels for open-cell PVDF foams before and after thermal annealing and electrical poling.

FIG. 5. Schematic illustration of (a) an open-cell PVDF foam and (b) mechanisms of acoustic energy absorption with polar β -phase.

After taking into account the effects of local polarization and local piezoelectric response, Fig. 5 schematically illustrates the noise absorption mechanisms in open-cell PVDF foams. When the acoustic wave strikes an open-cell porous material, the sound pressure wave penetrates deeply inside the materials and the interactions between the fluid and the solid occurs causing an energy transfer from the fluid to the solid structure. As a consequence, the mechanical energy in the acoustic wave of the fluid is absorbed and eventually converted into heat. In addition to the conventional visco-inertial, thermal and materials damping effects, the thin and polar struts of PVDF with the polar β -phase have at least another two effects: (1) the mechanical vibration excited by the acoustic wave is partially damped by being converted to electricity through the local piezoelectric effect and finally to thermal energy and (2) the friction and viscous loss at the fluid-solid interface may be enhanced in the presence of electrical charges. Thus, the enhancement in the polar β -phase and local piezoelectricity in the open-cell porous PVDF foam after annealing significantly improved the acoustic absorption performance. Hence, open-cell PVDF polymer foams with high content of polar β -phase have great potential for noise mitigation applications.

In summary, open-cell foams of simplified PVDF homopolymer composition with different content of polar β -phase were produced, and their airborne noise mitigation performance properties were investigated comparably. A thermal treatment was applied to the PVDF foams to enhance the polar β -phase content and thus the local piezoelectric effect. The experimental results and theoretical analysis showed that the existence of the polar phase and the local piezoelectric effect significantly improved the acoustic absorption coefficient of PVDF polymer foams. In addition to the conventional visco-inertial, thermal and materials damping effects, the thin and polar struts of PVDF foams with polar phase and the local piezoelectric effect may further enhance the mechanical damping by converting the excited mechanical vibration to electricity through the local piezoelectric effect and increasing the friction and viscous loss at the fluid-solid interface in the presence of electrical charges. Thus, the open-cell polymer foams with high content of polar phase and local piezoelectric effect have great potential for passive airborne noise mitigation applications.

See [supplementary material](#) for experimental details of foam preparation and characterization.

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- ¹C. M. Harris, *Handbook of Acoustical Measurements and Noise Control*, 3rd ed. (McGraw-Hill, New York, 1991).
- ²X. Sagartazu, L. Hervella-Nieto, and J. M. Pagalday, *Arch. Comput. Methods Eng.* **15**, 311 (2008).
- ³T. D. Northwood, *J. Acoust. Soc. Am.* **73**, S41 (1983).
- ⁴F. Han, G. Seiffert, Y. Zhao, and B. Gibbs, *J. Phys. D: Appl. Phys.* **36**, 294 (2003).
- ⁵G. Ballou, *Handbook for Sound Engineers*, 3rd ed. (Elsevier/Focal Press, Amsterdam, 2008).
- ⁶M. A. Biot, *J. Acoust. Soc. Am.* **28**, 168 (1956).
- ⁷M. A. Biot, *J. Acoust. Soc. Am.* **28**, 179 (1956).
- ⁸C. Zwikker and C. W. Kosten, *Sound Absorbing Materials* (Elsevier, New York, USA, 1949).
- ⁹D. L. Johnson, J. Koplik, and R. Dashen, *J. Fluid Mech.* **176**, 379 (1987).
- ¹⁰D. Lafarge, P. Lemarinier, J. F. Allard, and V. Tarnow, *J. Acoust. Soc. Am.* **102**, 1995 (1997).
- ¹¹J. F. Allard and N. Atalla, *Propagation of Sound in Porous Media: Modeling Sound Absorbing Materials*, 2nd ed. (John Wiley and Sons, Chichester, UK, 2009).
- ¹²R. F. Lambert, *J. Acoust. Soc. Am.* **73**, 1131 (1983).
- ¹³R. F. Lambert, *J. Acoust. Soc. Am.* **73**, 1139 (1983).
- ¹⁴M. Yang, S. Y. Chen, C. X. Fu, and P. Sheng, *Mater. Horiz.* **4**, 673 (2017).
- ¹⁵M. Yang and P. Sheng, *Annu. Rev. Mater. Res.* **47**, 83 (2017).
- ¹⁶M. C. M. Wright, *Lecture Notes on the Mathematics of Acoustics* (Imperial College Press, London, UK, 2005), pp. 157–176.
- ¹⁷J. P. Arenas and M. J. Crocker, *Sound Vib.* **44**, 12 (2010).
- ¹⁸M. O'Donnell, E. T. Jaynes, and J. G. Miller, *J. Acoust. Soc. Am.* **69**, 696 (1981).
- ¹⁹J. Mei, G. Ma, M. Yang, Z. Yang, W. Wen, and P. Sheng, *Nat. Commun.* **3**, 756 (2012).
- ²⁰Z. Liu, X. Zhang, Y. Mao, Y. Y. Zhu, Z. Yang, C. T. Chan, and P. Sheng, *Science* **289**, 1734 (2000).
- ²¹S. A. Cummer, J. Christensen, and A. Alù, *Nat. Rev. Mater.* **1**, 16001 (2016).
- ²²M. D. Guild, V. M. García-Chocano, W. Kan, and J. Sanchez-Dehesa, *J. Appl. Phys.* **117**, 114902 (2015).
- ²³S. M. Yang and J. W. Chiu, *Compos. Struct.* **25**, 381 (1993).
- ²⁴A. Blanguernon, F. Léné, and M. Bernadou, *Smart Mater. Struct.* **8**, 116 (1999).
- ²⁵V. Balamurugan and S. Narayanan, *Smart Mater. Struct.* **10**, 173 (2001).
- ²⁶M. Sumita, H. Gohda, S. Asai, K. Miyasaka, A. Furuta, Y. Suzuki, and K. Uchino, *Makromol. Chem., Rapid Commun.* **12**, 657 (1991).
- ²⁷W. Akl and A. Baz, in *Inter-Noise and Noise-Con Congress and Conference Proceedings* (2002), Vol. 5, p. 731.
- ²⁸M. Rahimabady, E. C. Statharas, K. Yao, M. S. Mirshekarloo, S. Chen, and F. E. H. Tay, *Appl. Phys. Lett.* **111**, 241601 (2017).
- ²⁹J. E. Unosson, C. Persson, and H. Engqvist, *J. Biomed. Mater. Res., Part B* **103**, 62 (2015).
- ³⁰A. J. Lovinger, *Macromolecules* **15**, 40 (1982).
- ³¹I. M. Daniel and J. M. Cho, *Exp. Mech.* **51**, 1395 (2011).
- ³²K. Uchino and T. Ishii, *J. Ceram. Soc. Jpn.* **863**, 96 (1988).
- ³³M. C. Araújo, C. M. Costa, and S. Lanceros-Méndez, *J. Non-Cryst. Solids* **387**, 6 (2014).