Sound Absorption of Nanofibrous Membranes

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The standardized characterization of nanofibrous membranes used to coat three porous bulk acoustical materials (melamine foam, a polyester fleece, and an MDF perforated panel) is presented in order to offer sustainable alternatives to predominantly used glass, mineral, and ceramic fibrous materials. The membranes were manufactured from recyclable Polyamide 6 and water-soluble Polyvinyl Alcohol using the needleless electrospinning technique. This resulted in very thin membranes of high porosity and very high airflow resistivity. Both an impedance tube and reverberation room measurements showed significant improvements in the sound absorption performance of the bulk materials after incorporating the nanofibrous layer on them.

Klíčová slova: sound absorption, nanofibrous, permeable membrane, electrospinning

Preface

As we can daily meet with various achievements of new technologies, in last few decades we also become more familiar with nanotechnologies. The nanotechnology field consist of multidisciplinary approaches how to deal with matter on a nanoscale and through its control ultimately change its properties substantially. There is a justified need in the acoustic market to incorporate sustainable materials as alternatives to glass, mineral, and ceramic fibrous materials, which have high carbon footprints [1]. Thus, a thin layer of nanofibrous material can be added to a standard bulk sound-absorbing material in the form of an attached membrane. Such layers are commonly used for the protection and structural integrity of the material. However, since this layer must be permeable in order not to degrade the acoustic performance, the membrane can also add acoustic resistance to the overall system, providing an increase in the total sound absorption. Therefore, a nanofibrous layer with its unique properties has the potential to work well as a thin, lightweight absorbing solution. It can be successfully applied in numerous areas, including room acoustics and construction, automotive, transportation, aerospace, and, interestingly today, as a solution to reduce noise coming out of drones [1–2].

Contrary to conventionally used microscale sound absorbers, sound absorbing membranes based on submicron fibers may show higher sound absorption abilities. As the membrane is forced to vibrate by incident sound waves, there are several physical mechanisms contributing to sound absorption. The kinetic energy of the membrane is transformed into thermal energy due to the friction between individual fibers, as well as the friction of the membrane with air and possibly with other layers of material arranged in its proximity. A certain part of the energy can also be transmitted to the frame (if it is present). In addition, part of the energy can be absorbed by scattering from the fibers and by the vibration caused in individual fibers or fiber segments (considering structural overlaps) [3]. These unique properties come from the nature of nanofibrous layers, i.e., their small fibrous diameter, correspondingly high specific surface area, and high values of porosity close to unity. This causes high viscous losses inside the material and, consequently, more dissipation of acoustic energy. Furthermore, due to resonance at its natural frequency, the membrane is able to absorb low-frequency sound energy. Nanofibrous elements and optimal rigidity of the membrane can lead an acoustic system to vibrate more efficiently [4,5].

Methodology

The theoretical basis of the sound absorption characteristics of a membrane sound absorber has been presented by Sakagami et al. in nineties [6]. To analyze the absorption mechanism, the solution is approached in a form that points out the contribution from each element of a membrane. Kalinová [4] has demonstrated that the nanofibrous layer has a resonant effect on sound absorption when the nanofibers are arranged with respect to the layer. It was reported that the sound absorption coefficient of a material composed of a nanofibrous web is significantly higher at lower frequencies than that of the basic material without nanofibers. It was also shown how the resonance frequency of a polyvinyl alcohol (PVA) nanofibrous membrane changed with its area density and the nanofibrous average diameter. The effectiveness of a fiber-based sound absorption material involves several parameters such as porosity, tortuosity, fiber diameter, surface density, and thickness [7].

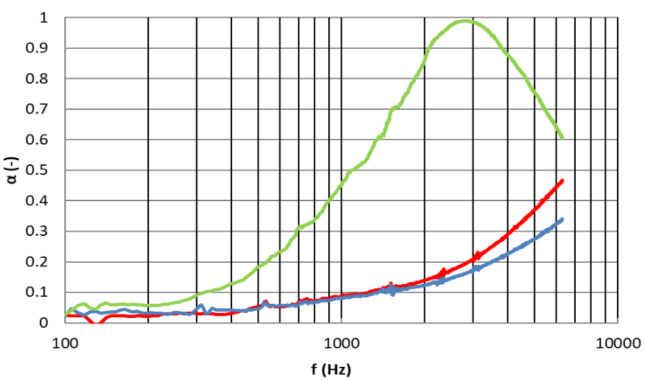
Thus, two polymer candidates were chosen in the course of this work within a scope of sustainable options. Polyamide 6 (PA6) has been described in several studies that have emphasized its potential application as an excellent recyclable polymeric material [8]. As a representative of a water-soluble polymer, polyvinyl alcohol (PVA) has been selected.

Both the fiber morphology and the fiber diameter of the electrospun nanofibers were determined using scanning electron microscopy (SEM). Characterization of non-acoustical properties also involved: airflow resistivity, air-permeability, pore size, porosity, and surface area determination.

The normal-incidence sound absorption coefficient was measured in the frequency range 50 to 6400 Hz using a two-microphone impedance measurement tube (Brüel & Kjær Type 4206). In addition, some materials were also tested in a reverberation room (sound diffuse field) to obtain the statistical sound absorption coefficients for one-third-octave frequency bands between 100 and 5000 Hz.

Results

It can be noticed that the sound absorption performances of the bulk material with and without the micro-fibrous substrate are similar, where the bulk material with the substrate exhibits a slight improvement in high frequencies. This is obvious given the high air permeability of the nonwoven textile substrate. However, the effect of incorporating the nanofibrous membrane on the sound absorption properties is remarkable. This effect can be explained by the increase in the real part of the surface impedance of the bulk material when the nanofibrous membrane is attached on top of it. This added resistance is approximately given by the airflow resistivity of the membrane times its thickness, as explained in [9]. A significant increase in the sound absorption coefficients is clearly observed for frequencies above 1 kHz when the nanofibrous membrane is added to the fibrous bulk material. A maximum sound absorption value near unity is achieved at around 3 kHz (Pic. 1).



Pic. 1: Normal-incidence sound absorption coefficient as a function of frequency for the 8mm PET non-woven fibrous bulk absorber alone (blue line), treated just with a micro-fibrous substrate (red line) and treated with the 0.2 gsm PA6 nanofibrous membrane on this substrate (green line).

Conclusion

The sound absorption coefficient results measured in an impedance tube show that a significant improvement in the sound absorption performance of the bulk materials or traditional air-backed perforated panel can be achieved by incorporating the nanofibrous layer on them. Results of the sound absorption coefficient from a reverberation room also report a substantial increase. These high values were received after treating low thickness materials. This is of great importance in satisfying the transportation industry aims of high sound absorption values with reduced weight to reduce fuel consumption! Hence, further application of these membranes to recycled bulk materials has the potential to result in more ecological acoustic materials. Let's emphasize here that there is a clear theoretical gap in the prediction of a nanofibrous structure acoustical properties. However, this is far from easy to carry out [10].

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References

[1] Arenas, J.P.; Crocker, M.J. Recent trend in porous sound-absorbing materials. *Sound Vib*. 2010, *44*, 12–17.

[2] Beckermann, G.; Hosie, I.; Clarke, A.; Rowe, M.; Rowe, S.; Pentecost, S.; Edlin, S. Sound attenuating performance of nanofiber materials used in unmanned aerial vehicles. *Adv. Mat.: TechConnect Briefs* 2018, 212-215.

[3] Dahl, M.D.; Rice, E.J., Groesbeck, D.E. Effects of fiber motion on the acoustical behavior of an anisotropic, flexible fibrous material, *J. Acoust. Soc. Am*. 1990, *87*, 54-66.

[4] Kalinova, K. Nanofibrous resonant membrane for acoustic applications. *J. Nanomaterials* 2011, *2011*, ID 265720.

[5] Asmatulu, R.; Khan, W.; Yildirim, M.B. Acoustical properties of electrospun nanofibers for aircraft interior noise reduction. In *Proceedings of the ASME 2009 International Mechanical Engineering Congress & Exposition*, 2009, *15*, 223–227.

[6] Sakagami, K.; Kiyama, M.; Morimoto, M.; Takahashi, D. Sound absorption of a cavity-backed membrane: A step towards design method for membrane-type absorbers. *Appl. Acoust*. 1996, *49*, 237–247.

[7] Seddeq, H.S. Factors influencing acoustic performance of sound absorptive materials. *Australian J. Basic Appl. Sc.* 2009, *3*, 4610–4617.

[8] Singh, R.; Kumar, R.; Ranjan, N.; Penna, R.; Fraternali, F. On the recyclability of polyamide for sustainable composite structures in civil engineering. *Composite Struct*. 2018, *184*, 704-713.

[9] Chevillotte, F. Controlling sound absorption by an upstream resistive layer. *Appl. Acoust*. 2012, 73, 56-60.

[10] Horoshenkov, K.V.; Hurrell, A.; Jiao, M.; Pelegrinis, M.T. What is the actual influence of a nano-fibrous membrane on the acoustical property of porous substrate? *Proc. Institute Acoust*. 2018, *40*, Part 1.