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Effect of Fiber Diameter and Air Gap on Acoustic Performance of Nanofibrous Membrane

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Abstract: The absorption of sound in the low frequency range is problematic with fibrous materials made up of coarser fibers. In that case, highly efficient sound absorption materials from much finer fibers must be developed. Although studies on the acoustic properties of conventional textile materials started in the nineties, analysis of the acoustic properties of the electrospun nanofibrous membranes is a novel subject. Nanofibrous membranes can improve acoustic insulation products by increasing the sound absorption coefficient, reducing material thickness, and decreasing material weight offering a competitive advantage. The purpose of this study is to analyze the effect of fiber diameter on the acoustic behavior of nanofibrous membranes.

Key words: Electrospun nanofibrous membrane, acoustic characteristic, fiber diameter.

1. Introduction

Highly efficient sound absorption materials derived from finer fibers are required to absorb lower frequency sound. A study on the sound absorption of PVA (polyvinyl alcohol) nanofibrous resonant acoustic membranes showed that the resonant frequency of the nanofibrous membrane decreased with increasing area density of the membrane and increased with decreasing average diameter of the nanofibers [1]. Kalinova [2, 3] proved that the nanofibrous materials are highly efficient sound absorbers. For low-frequency absorption, structures based upon the resonance principle are employed in which the resonance of some elements allows acoustic energy to be converted into thermal energy. Kalinova [4] also studied sound absorption behavior of PVA nanofibrous membrane with different structures. Water vapour was applied to the surface of nanolayers (for 10 to 120 s) in order to change the structure of membranes containing nanofibers. Sound absorption coefficient of thin PVA nanofibrous membranes and foil was compared with each other. The result of the experimental study showed that the shapes of frequency functions are analogical for thin polymeric foil as well as for nanofiber PVA membrane. Furthermore, as the time of water vapour action to PVA nanofibers layer is increased, the number of local place with different mass increased and merged fibers should increase too which resulted in an increase in the absorbed frequency range. In another study on the comparison of sound absorption behavior of nanofibrous layer and polyethylene foil with the same area weight, she found that nanofibrous layer had higher sound absorption coefficient than foil. Moreover, an increase in the area weight and size of air gap between the membrane and rigid wall provided an increase in the sound absorption coefficient [5]. There are also other reports [6-8] on the acoustic properties of nanofibrous membranes. Sound absorbents based on nanofibers can have a higher absorption factor compared to traditional absorbents especially in lower frequencies. The aim of this study was to discuss the sound absorption and transmission loss performance of nanofibrous resonant membranes

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having different fiber diameters which were produced from PVA solution using a needleless electrospinning process. The sound absorption properties of those membranes were comparatively discussed. Furthermore, the effect of the air gap between the nanofibrous membrane and a rigid wall on the sound absorption coefficient was also analyzed.

2. Experimental Study

2.1 Material

For the production of nanofibrous membrane: The water solution of PVA (M_w = 80,000-100,000 g/mol) was employed. Glyoxal and phosphoric acid were added as crosslinking agents. The content of glyoxal (40% w/w) to PVA was 6% v/v and the content of phosphoric acid (85% w/w) to PVA was 3% v/v. The solution containing PVA, distilled water, glyoxal, and phosphoric acid was vigorously stirred at room temperature. PVA solution was prepared having a concentration of 12.8% v/v. PVA solution of 14% v/v was also prepared by decreasing the water content in the solution. The amount of crosslinking agents was determined based on the recipe proposed by Eva et al. [9] where used higher amount of crosslinking agents for better crosslinking of PVA nanofibers.

2.2 Membrane Production

For the production of PVA nanofibrous membranes, roller electrospinning method was employed [10].

In needleless (roller) electrospinning (schematic diagram in Fig. 1, a slowly rotating roller partially is immersed in polymer solution. Polymer solution is connected to a high voltage source. Collector is usually grounded. In electrospinning process, polymer solution is taken to the surface of the roller because of its rotation. With suitable high voltage, many Taylor cones are simultaneously created on the roller surface, producing nanofibers. The nanofibers are then transported towards the collector.

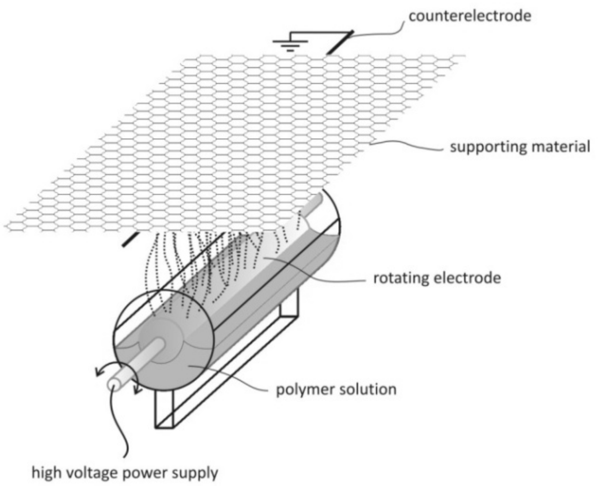

Fig. 1 Schematic diagram of roller electrospinning method used for nanofibrous membrane production.

Table 1 Process parameters for $PVA_{12.8}$ membrane production.

Roller length (mm)	145
Roller diameter (mm)	20
Roller angular velocity (rpm)	2
Distance between electrodes (mm)	120
Source voltage (kV)	50
Relative humidity (%)	34
Temperature (^{o}C)	19

Optimum process parameters such as roller speed, distance between the electrodes, voltage etc.. were applied during the spinning process. Niu et al. [11] found that the minimal collecting distance for the PVA solution was 11 cm. A cylinder spinneret had different critical voltages for initiating electrospinning and an increase in the applied voltage from 47 to 62 kV had little effect on the average fiber diameter in cylinder electrospinning systems. A good balance should be maintained between the applied voltage and the collecting distance for a successful upward needleless electrospinning. Therefore, the process parameters were set as shown in Table 1.

In an attempt to increase the fiber diameter, the other resonant membrane was produced from a PVA solution having a concentration of 14% by keeping the process parameters presented in Table 1 constant. Studies on PVA nanofibers also indicated that fiber diameter shows an increase with an increase in the polymer concentration [12, 13].

2.3 Characterization

The surface and structure of the membrane and the diameter of the electrospun PVA fibers were determined using a Carl Zeiss Ultra Plus Field SEM (scanning electron microscopy). The average fiber diameter was calculated from the SEM images using image analysis software (NIS Elements BR 3.2).

2.4 Methods

2.4.1 Measurement of Sound Absorption Coefficient of Nanofibrous Resonant Membranes Developed

Two-microphone Impedance Measurement Tube Type 4206 was used to measure the absorption coefficient in the frequency ranges 50 Hz to 6.4 kHz. The test was made according to standard ASTM E1050−08.

PULSE software was used for acoustic analysis [15]. The maximum value of the sound absorption coefficient coincides with the resonance frequency peak of the thin membrane. Sound waves vibrate the resonant nanofibrous system, with acoustic energy at the resonance frequency (Fig. 3) then partially converted to kinetic energy, the remainder being acoustic energy at other frequencies. These frequencies are damped so that the majority of the acoustic energy, accumulated in the resonator, may be converted to heat.

In order to analyze the effect of the air gap size on the sound absorption behavior of the samples, air gap of 5, 10 and 15 mm was left between the sample and the rigid wall (Fig. 4).

2.4.2 Measurement of Sound Transmission Loss of Nanofibrous Resonant Membranes Developed

In this study, the TL (transmission loss) of the exhaust system was measured using 4 microphone impedance tube, based on the idea calculating the full transfer matrix of the acoustical sample to be tested. The test was conducted according to the standard ASTME 2611−09.

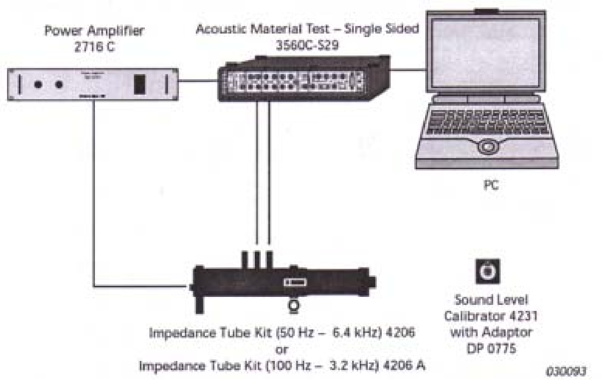

Fig. 2 Impedance tube setup.

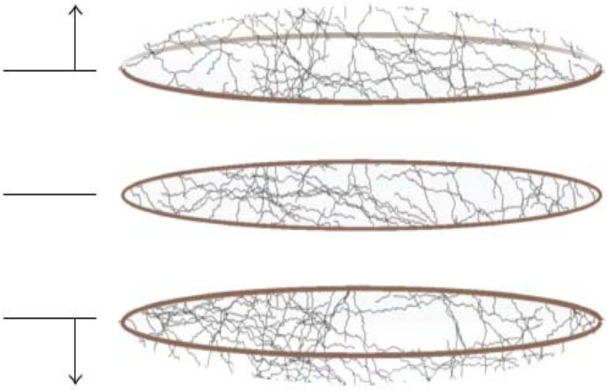

Fig. 3 Nanofibrous membrane vibration at the first resonance frequency.

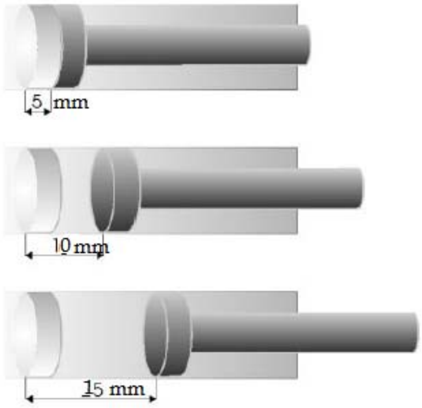

Fig. 4 Different sizes of air gaps between the sample and the rigid wall for the membrane sample.

2.5 Experiment Set-Up

The impedance tube, which has the sample holder, four microphones, loudspeaker, and acoustic terminator were used for this measurement [14]. Two microphones were located to the source room, i.e., the right side of the acoustic specimen, and the other two microphones were located in the receive room, i.e., the other side of the specimen. All those microphones were connected to the FFT (fast fourier transform) analyzer, i.e.. PULSE generates the random signal to the loudspeaker, which was attached on the end of the impedance tube. The sound signals captured from the four microphones were simultaneously measured and processed in the FFT analyzer. The system configurations are shown in Fig. 5 [16]. Also the user-interface software is composed on top of PULSE platform.

2.6 Experiment Procedure

In order to compensate the phase mis-match among the four microphones, the transfer functions factor was utilized to get the transmission loss coefficient with four microphones. After the phase correction among the four microphones, the transfer functions were simultaneously measured in each microphone positions with variations of the boundary conditions of the impedance tube end, i.e., open and closed conditions. Finally, the transmission loss coefficient was calculated using the measured transfer functions. Schematic diagram of the impedance tube for measuring the sound transmission loss is shown in Fig. 6 [17].

3. Results and Discussion

The average fiber diameters of the nanofibrous membranes were found to be 210 ± 40 nm and 300 ± 40 nm from $PVA_{12.8}$ and from PVA_{14} respectively (Fig. 7).

The following figures (Figs. 8-11) show the sound absorption properties of PVA_{14} and $PVA_{12.8}$ nanofibrous membranes having different fiber diameters and same mass per unit area (5 g/m^2) for different air gap settings. As can be seen in those figures, the sound absorption coefficients were improved when finer fibers were used, thanks to the nano dimensions of the interfiber areas and increased surface area among the fibers which has a positive effect on the sound absorption property. On the other hand, the occurrence of the first peak during the sound absorption coefficient measurements followed a decreasing tendency with the increase in the fiber diameter. The graphs also showed that the sound absorption coefficients increased with increasing the air gap between the membrane and the rigid wall from 5 mm to 15 mm. This might be due to the increased vibration potential of the PVA nanofibrous membranes under the influence of the incident sound wave. No space is left to the membrane to vibrate when it is adjacent to the wall. With the presence of the air gap, the membrane can more easily vibrate and dissipate the acoustic energy to heat.

Fig. 12 shows sound transmission loss values of PVA_{14} and $PVA_{12.8}$ nanofibrous membranes. As can be seen in Fig. 12, there is not any significant difference between the transmission loss values of the membranes. The effect of the fiber diameter on the transmission loss could not be observed because of the extremely thin structure of the nanofibrous membranes.

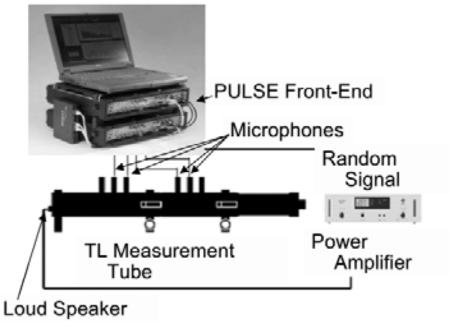

Fig. 5 Experiment system configuration of TL measurement.

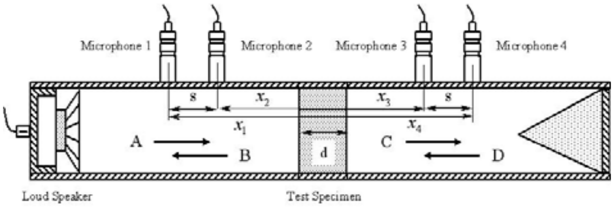

Fig. 6 Schematic diagram of the impedance tube for measuring the TL.

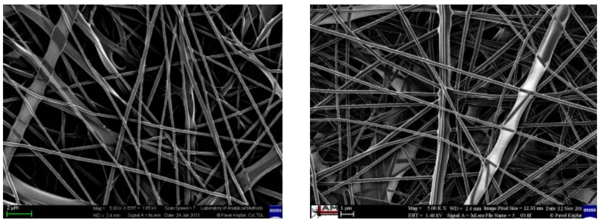
(a) (b)

Fig. 7 SEM images of (a) $PVA_{12.8}$ and (b) PVA_{14} nanofibrous membranes.

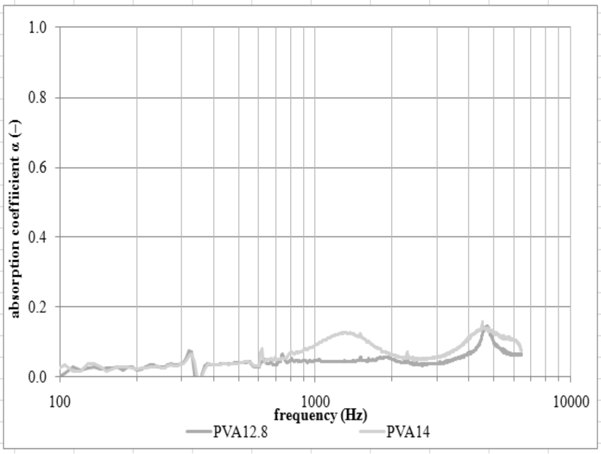

Fig. 8 Measured sound absorption coefficient (α) of PVA$_{12.8}$ and PVA$_{14}$ nanofibrous membranes as a function of sound frequency.

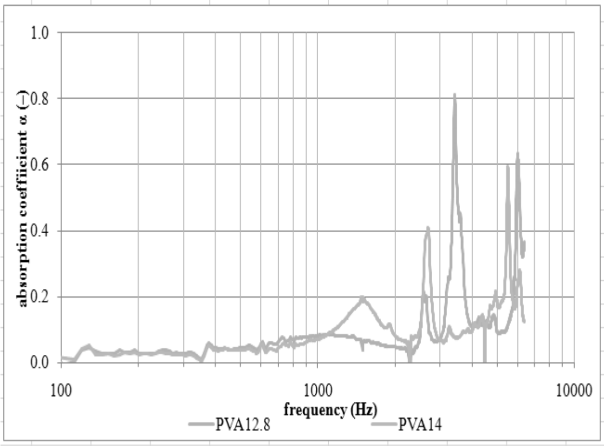

Fig. 9 Measured sound absorption coefficient (α) of PVA$_{12.8}$ and PVA$_{14}$ nanofibrous membranes as a function of sound frequency f with 5 mm air gap.

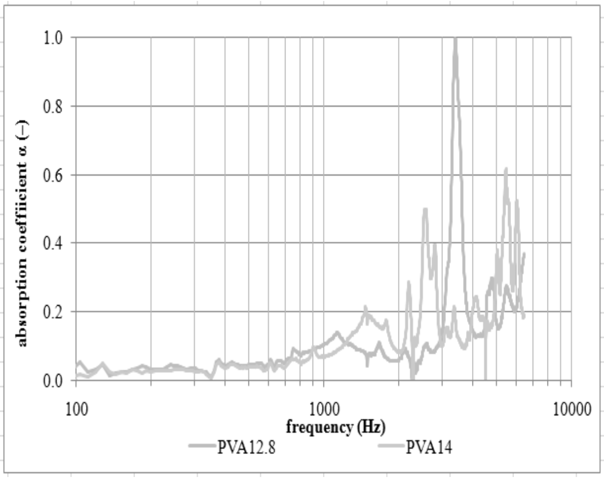

Fig. 10 Measured sound absorption coefficient (α) of PVA$_{12.8}$ and PVA$_{14}$ nanofibrous membranes as a function of sound frequency f with 10 mm air gap.

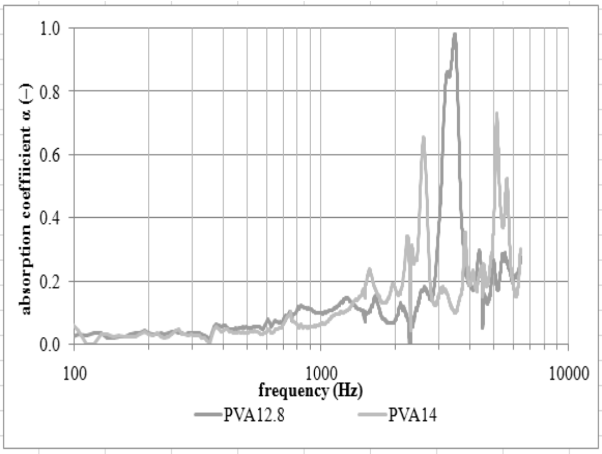

Fig. 11 Measured sound absorption coefficient (α) of PVA$_{12.8}$ and PVA$_{14}$ nanofibrous membranes as a function of sound frequency f with 15 mm air gap.

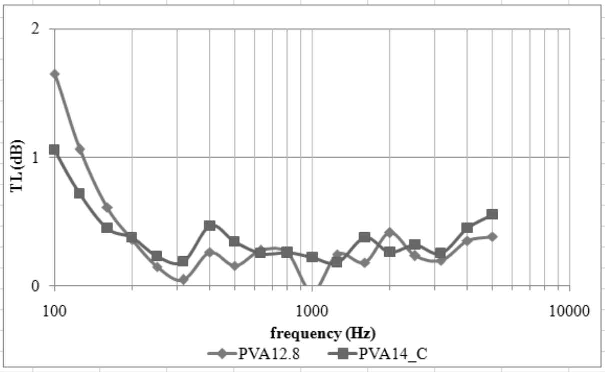

Fig. 12 Measured TL of PVA$_{12.8}$ and PVA$_{14}$ nanofibrous membranes as a function of sound frequency.

4. Conclusions

Resonant absorption provides good sound absorption at lower-frequencies. The sound absorption behavior of the nanofibrous membranes increased when the fiber diameter was decreased and when the air gap between the sample and a rigid wall was increased. Moreover, there is not any significant difference between the transmission loss values of the membranes.

It may be concluded that the nanofibrous membranes would offer efficient solutions to the noise problems in low frequency ranges.

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