Acoustical and non-acoustical behaviour of nanofibers membranes

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1 Introduction

There is a general lack of publications on the acoustical and related non-acoustical properties of nanofibrous media. This work attempts to contribute to this gap and to highlight problems associated with acoustic and related non-acoustic characterisation of these materials. It makes use of Biot- and Darcy-type mathematical models to explain the observed acoustical and related non-acoustical behaviours of the nanofibres. It identifies theoretical gaps related to the physical phenomena which can be responsible for the observed acoustical behaviours of nanofibrous membranes and it presents recommendations to fill these gaps. The novelty of this work is in the application of a robust theoretical model to explain the measured acoustical behaviour of thin nanofibrous membranes placed on a foam substrate. With this model the actual flow resistivity of nanofibers is estimated from acoustical data. It is demonstrated that a classical model for the flow resistivity of fibrous media does not work when the Knudsen number becomes greater than 0.02, i.e. then the diameter of nanofibres becomes comparable with the mean free path.

2 Material preparation

19 membrane samples were electrospun using in-house built single-needle electrospinning rigs at the University of Surrey and the University of Sheffield. Pump-rates were tailored to each solution, voltage, and atmospheric conditions, increasing the rate to the maximum possible before unwanted dripping from the spinneret was observed. This ensured a stable, steady stream of polymer for optimum nanofibre production in the fibre diameter range of 281 – 3630 nm and membrane thickness of 5.41 – 32.38 μm.

3 Material characterisation

The acoustical properties of the fibrous membranes were measured at the University of Sheffield in the 45 mm impedance tube in the presence of the melamine foam substrate. The 3-parameter model for the acoustical properties of porous media [1] was used to fit the measured complex acoustic reflection coefficient of melamine foam. The fibre diameter was measured using SEM images. The fibre density and porosity were measured directly from sample volume and mass information. The acoustical and related non-acoustical properties of nanofibrous media were inverted from the complex reflection coefficient data measured in the frequency range of 300 and 300 Hz.

4 Results

Figure 1 illustrates the effect of a 22 μm thick, 15 kV PMMA nanofibrous membrane on the complex reflection coefficient of the melamine foam substrate. The continuous lines correspond to the predictions by the model detailed in ref. [1] and markers correspond to the measured data. The presence of a very thin nanofibrous membrane causes a significant reduction in the real and imaginary parts of the reflection coefficient. This effect is explained by the increase in the real part of the surface impedance of the melamine foam substrate when the thin, nanofibrous layer is added on the top it.

According to the Kozeny-Carman model [2] the relation between the flow resistivity, σ, and fibre diameter, $\underline{d}$, is:

$$\frac{\sigma \underline{d}^2}{\eta} = \frac{180(1-\phi)^2}{\phi^3}. \quad (1)$$

Here η is the dynamic viscosity of air. The Kozeny-Carman model works well to predict the flow resistivity of highly porous media composed of fibres with the diameter of a few microns [2]. However, it is interesting to check if it also works for fibrous media made of nanofibres. To the best of our knowledge this has not been done before for flow velocities through the fibres which are comparable with the acoustic velocity in the audible range.

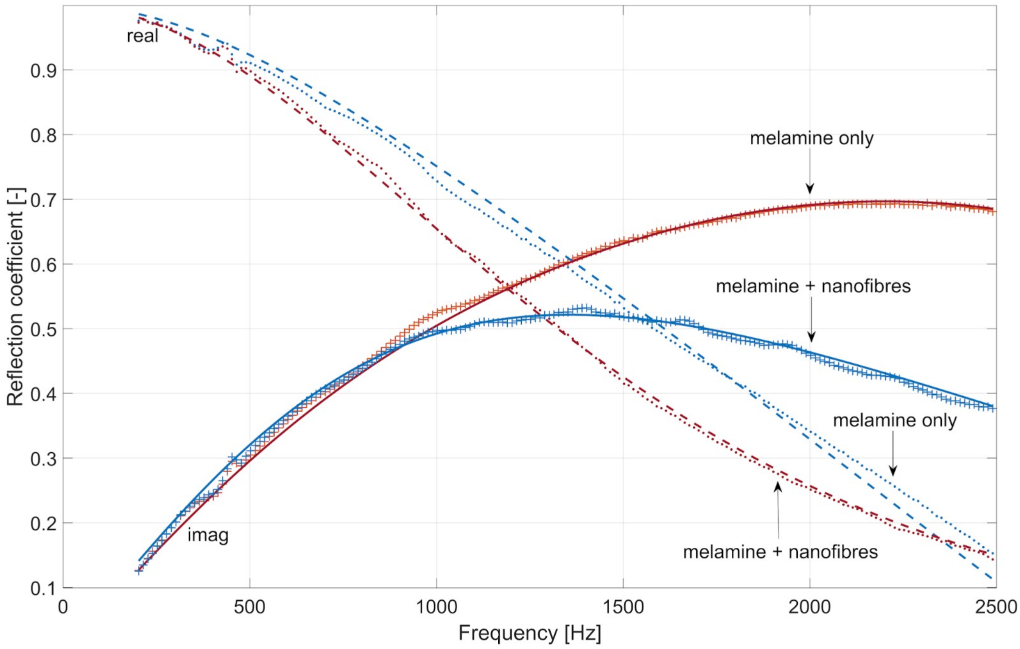

Figure 1 : The effect of nanofibrous membrane on the real and imaginary part of a 16 mm thick layer of melamine foam. Lines correspond to the theoretical fit, dots and crosses correspond to the measured data.

Let us denote the left- and right-hand parts of eq. (1) as:

$$f_1(\sigma, \underline{d}) = \frac{\sigma \underline{d}^2}{\eta}, \tag{2}$$

and

$$f_2(\phi) = \frac{180\left(1-\phi_{nf}\right)^2}{\phi_{nf}^3}, \tag{3}$$

respectively. We can call these two functions the flow resistivity, $f_1(\sigma)$, and porosity, $f_2(\phi_{nf})$, terms, respectively.

The work by Umnova et al [3] suggests that the flow resistivity of in eqs. (2) and (3) needs to be compensated for the so-called no-slip effects when the fibres diameter, $\underline{d}$, becomes comparable tof mean free path, l. According to this work the flow resistivity of nanofibres compensated for no-slip condition is (eq. (46) in [3]:

$$\sigma_{\perp} = \frac{\sigma}{1+\frac{4K_n}{1+2K_n}F\left(\phi_{nf}\right)}, \tag{4}$$

where

$$F(\phi_{nf}) = \frac{\phi_{nf}^2}{-2\ln\ln(1-\phi_{nf}) - 2\phi_{nf} - \phi_{nf}^2} \quad (5)$$

and σ is predicted by eq. (1). It is logical to assume that functions (2) and (3) should be equal if eq. (1) holds for nanofibres.

Let us now use eqs. (2)-(4) to check how eq. (1) holds for nanofibres. Figure 2 graphically illustrates the dependence of these functions on the Knudsen number, $K_n = \frac{l}{\underline{d}}$, where l=68 nm is the mean free path in air. If eq. (1) were to hold true, then the two sets of data shown in Figure 2 would be close to the solid black line which corresponds to the value of $f_2(0.8)$; $\phi_{nf}=0.8$ is a typical value of porosity fibrous media made from relatively large fibres. According to Figure 2 this seems only the case for fibres with relatively large mean diameters, i.e. for $K_n \approx 0.02$. As the fibre diameter decreases, the difference between the values of $f_1(\sigma_{nf}, \underline{d})$ and $f_2(\phi_{nf})$ becomes greater. The flow resistivity of nanofibres decreases with an increase in K_n. On the other hand, the function $f_2(\phi_{nf})$ grows with an increase in K_n. This suggests that equation (1) no longer holds for $K_n > 0.02$ or for smaller fibre diameters. The compensation for nonslip conditions (eq. (4)) does not explain the drop in the flow resistivity of nanofibres with an increase in K_n (stars in Figure 2). The stars in Figure 2 show that the difference between the flow resistivity compensated for noslip conditions, $\sigma_{\perp}$, and measured flow resistivity, σ_{nf}, becomes more than one order of magnitude when the Knudsen number becomes greater than 0.1.

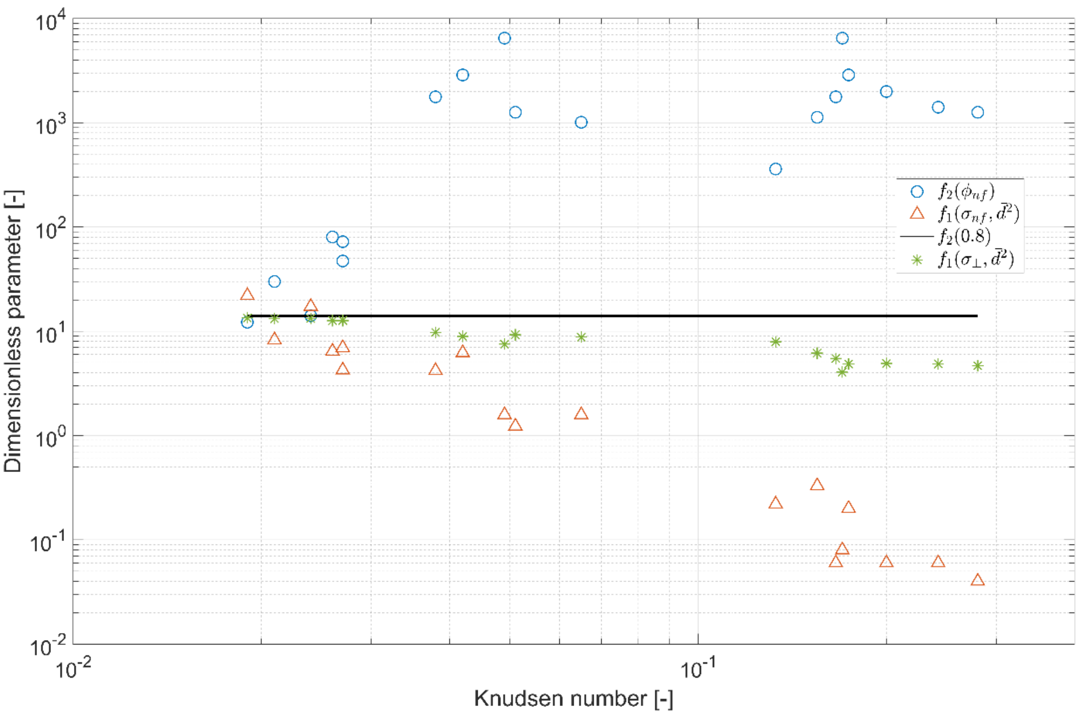

Figure 2 : The normalised flow resistivity and porosity terms in the Kozeny-Carman equations predicted for the parameters of nanofibrous media developed in this work.

References

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