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An Inverse Method to Obtain Porosity, Fibre Diameter and Density of Fibrous Sound Absorbing Materials

Jesus ALBA[(1)], Romina del REY[(1)],
Jaime RAMIS[(2)], Jorge P. ARENAS[(3)]

[(1)] *Polytechnic University of Valencia*
Research Institute for Integrated Coastal Zone Management-IGIC
Grao de Gandia 46730 (Valencia), Spain
e-mail: jesalba@fis.upv.es
roderey@doctor.upv.es

[(2)] *University of Alicante*
Department of Physics, System Engineering and Signal Theory
Mail Box 99; 03080 Alicante, Spain
e-mail: jramis@ua.es

[(3)] *University Austral de Chile*
Institute of Acoustics
Campus Miraflores, PO Box 567, Valdivia, Chile
e-mail: jparenas@uach.cl

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Characterization of sound absorbing materials is essential to predict its acoustic behaviour. The most commonly used models to do so consider the flow resistivity, porosity, and average fibre diameter as parameters to determine the acoustic impedance and sound absorbing coefficient. Besides direct experimental techniques, numerical approaches appear to be an alternative to estimate the material's parameters. In this work an inverse numerical method to obtain some parameters of a fibrous material is presented. Using measurements of the normal incidence sound absorption coefficient and then using the model proposed by Voronina, subsequent application of basic minimization techniques allows one to obtain the porosity, average fibre diameter and density of a sound absorbing material. The numerical results agree fairly well with the experimental data.

Keywords: sound absorption, fibrous materials, porous material, material characterization.

1. Introduction

Fibrous materials have been widely used in noise control applications and most of the porous sound absorbing materials commercially available are fibrous

(Crocker, Arenas, 2007; Arenas, Crocker, 2010). Fibrous materials consist of a series of tunnel-like openings which are formed by interstices in material fibers.

Several models for predicting the acoustic behaviour of sound absorbing materials have been proposed in the technical literature (Kidner, Hansen, 2008). These models have been described in the time-domain, such as the one by Wilson (1997), as well as in the frequency-domain. The models defined in the time-domain are useful for studying transient behaviour. However, models intended to describe the acoustic behaviour of materials as a function of frequency are more common. Normally, these models allow us to obtain both the characteristic and propagation constant of the medium based on the physical parameters of the material. Among the various frequency-domain models reported in the literature, we can mention the one by Delany and Bazley (1970), Allard and Champoux (1992), Attenborough (1982, 1983) and Voronina (1994), which have been seminal for various subsequent studies. As mentioned above, these models seek to find a complete characterization of porous or fibrous materials based on different parameters, such as porosity, fibre density, material density, compressibility modulus, flow resistivity, structural form factor, tortuosity, etc. Each of these models has its own limitations and may only be used under certain conditions.

Nevertheless and generally speaking, the methods can be classified into two main groups: those that use the flow resistivity and those using porosity as relevant parameters. In the first group, we can cite the work by Delany and Bazley (1970) which is based on an empirical model and designed for fibrous absorbent materials, such as mineral wool. Additional improvements to this model have been presented by others authors. Some works that can be mentioned include those by Bies and Hansen (1980) that extended the lower and upper frequency ranges of validity over the Delany and Bazley model, the one by Miki (1990a; 1990b) which provided improvements of the coefficients proposed by Delany and Bazley, a model proposed for foam material (Dunn, Davern, 1986), a model for textile fibres (Garai, Pompoli, 2005), and a model proposed for natural fibres (Ramis *et al.*, 2010). Additional empirical studies have been presented by Wang *et al.* (2004), that is based on a regression of different variables, and by Shoshani and Yakubov (2000) which explores maximum absorption. The model proposed by Allard and Champoux (1992) uses specific flow resistivity in a physical model based on the complex density and complex compressibility moduli.

Among the models in the frequency-domain using porosity as a relevant parameter, the empirical model reported by Voronina has received much attention (Voronina, 1996; 1998; 1999; Voronina, Horoshenkov, 2003). Voronina presented several equations for acoustic impedance and the propagation constant in different situations. Some of the cases are: for high porosity fibrous materials (Voronina, 1994), improvements of the model for thinner fibres (Voronina, 1996), models for porous materials as a function of porosity for different situations or materials, etc. (Voronina, 1998; 1999; Voronina, Horoshenkov, 2003). Moreover, many of the cited authors make it clear that at high frequencies, the impedance and propagation constant of a material depend on both porosity and tortuosity.

Since porosity is one of the relevant high-frequency parameters, methods at high frequencies or in the ultrasonic range have been developed for its determination. Champoux *et al.* (1991) proposed a device for measuring porosity. The studies presented by Fellah and colleagues (Fellah *et al.*, 2003a; 2003b; 2003c) have used ultrasonic systems for measuring this parameter, among others. Umnova *et al.* (2005) have proposed measurements at high frequencies and in a range up to 20 kHz for fibres with thickness of more than 1 mm. Other studies have proposed inverse methods to obtain tortuosity, viscous and thermal characteristic lengths (Atalla, Panneton, 2005; Fellah *et al.*, 2007). More recently, a Bayesian theory has been used to improve the efficiency of an inverse method for identifying the acoustic and elastic parameters of poroelastic materials (Chazot *et al.*, 2010).

In this article an inverse method for determining the porosity, diameter and density of fibrous materials, from the measured values of sound absorption coefficient is presented. The inverse method is implemented using the Voronina formulation (Voronina, 1994), whereby the application conditions are limited to those indicated by this model, i.e. the model is exact enough for materials such that the product of frequency and fibre diameter is greater than 2.7×10^{-3}. The method measures the normal incidence sound absorption coefficient according to ISO 10534-2:1998 (ISO, 1998). The experimental basis taken to validate the method consist of two types of fibrous materials (Kenaf and Polyester), differing each sample in thickness and density, as we will see in the next section.

2. Approach

2.1. Theoretical model

Sound propagation through a homogeneous and isotropic material in the frequency domain is determined by two complex values, i.e., the complex propagation constant (Γ) and the complex impedance characteristic (Z):

$$\Gamma = \alpha + j\beta, \tag{1}$$

$$Z = R + jX. \tag{2}$$

As mentioned above, different frequency domain models exist. Some of these models use specific flow resistivity as a parameter. In the case that concerns us, it was decided to use the Voronina model (Voronina, 1994), which depends directly on the porosity H of the material.

Porosity is defined as the ratio of the void space within the material to its total displacement volume (Crocker, Arenas, 2007). It can be expressed as a function of the volumetric densities of the material, ρ_m, and the fibre, ρ_f, as

$$H = 1 - \frac{\rho_m}{\rho_f}. \tag{3}$$

The Voronina model uses analytical functions that vary with the porosity H of the material, the frequency f and the average fibre diameter d. The structural characteristic Q is given by the formula

$$Q = \frac{(1-H)(1+q_0)}{Hd}\sqrt{\frac{8\mu}{k\rho_0 c_0}}, \tag{4}$$

where $\mu = 1.85 \times 10^{-5}$ Pa·s is the dynamic viscosity coefficient of air, ρ_0 is the density of air, c_0 is the speed of sound in air, and q_0 is obtained from the following empirical expression

$$q_0 = \frac{1}{1 + 2 \times 10^4 (1-H)^2}. \tag{5}$$

The characteristic impedance (Z) and the propagation constant (Γ) are obtained from the structural characteristics by means of the equations

$$Z = \rho_0 c_0 (1 + Q - jQ), \tag{6}$$

$$\Gamma = k\frac{Q(2+Q)}{1+Q} + jk(1+Q), \tag{7}$$

where k is the free-field wavenumber $(2\pi f/c_0)$.

Equations (4) through (7) are valid in this model, only if the following condition is met

$$kd \times 10^4 > 0.5. \tag{8}$$

Equation (8) implies that the lower cut-off frequency validating the above expressions is

$$f > \frac{c_0}{4\pi d}10^{-4}. \tag{9}$$

Equation (9) states that if the fibre diameter is 10 μm (e.g. for mineral wool) the frequency must exceed 275 Hz. If the diameter is 36 μm (Polyester wool) the frequency should be greater than 76 Hz, and if it is 60 μm (Kenaf wool) then the frequency should be greater than 46 Hz. It can be seen that this model is based on purely theoretical parameters, and that it depends on the porosity.

We can rewrite Eq. (4) for the structural characteristic Q as

$$Q = \frac{Q_p}{\sqrt{k}}. \tag{10}$$

This change results in a new unknown Q_p, which does not depend on the frequency and should be constant for each material. Therefore

$$Q_p = \frac{(1-H)(1+q_0)}{Hd}\sqrt{\frac{8\mu}{\rho_0 c_0}} = \frac{(1-H)\left(1+\dfrac{1}{1+2\times 10^4(1-H)^2}\right)}{Hd}\sqrt{\frac{8\mu}{\rho_0 c_0}}. \tag{11}$$

Again, we can rewrite Eq. (11) as

$$Q_p = Q_H \frac{R}{d}, \tag{12}$$

where we have defined

$$Q_H = \frac{(1-H)\left(1+\dfrac{1}{1+2\times 10^4(1-H)^2}\right)}{H} \tag{13}$$

which depends only on the porosity, and

$$R = \sqrt{\frac{8\mu}{\rho_0 c_0}}, \tag{14}$$

that depends on air parameters.

2.2. Sound absorption coefficient and specific impedance

The experimental determination of the sound absorption coefficient for fibrous materials is usually carried out by using the standard ISO 10534-2:1998, which is employed to determine the sound absorption coefficient and the impedance of a material sample in an impedance tube using the transfer-function method (ISO, 1998). Experimental setup is well known and is shown in Fig. 1.

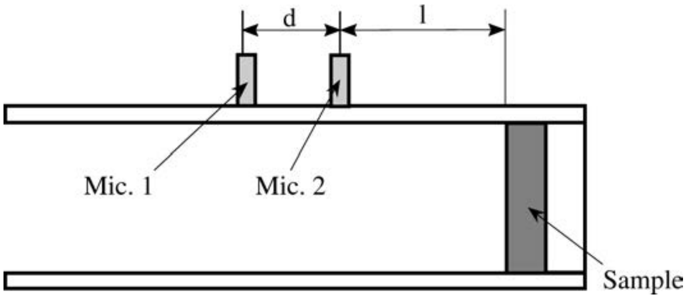

Fig. 1. Experimental setup suggested in the standard ISO 10534-2:1998.

By means of this standard we can obtain the normal incidence sound absorption coefficient α_n, and the material specific impedance Z'. From a theoretical point of view, if Eqs. (6) and (7) are assumed to be valid, the material specific surface impedance can be obtained from the following equation

$$Z' = Z_0 \coth(\Gamma e) = Z_R + jZ_I, \tag{15}$$

where Γ is the propagation constant of the sound absorbing material, e is the thickness of the sample, and Z_0 is the characteristic impedance of air. The normal incidence sound absorption coefficient is given by the ratio

$$\alpha_n = \frac{4Z_R Z_0}{|Z'|^2 + 2Z_0 Z_R + (Z_0)^2}. \tag{16}$$

The results of Eq. (16) and the measurements obtained according to the ISO standard must match, subject to certain limitations.

2.3. Inverse method description

In order to describe the method, we define a quadratic error function ϵ according to

$$\epsilon = \sum_{i=1}^{N} (\alpha_{n,i} - \widehat{\alpha}_{n,i})^2, \tag{17}$$

where $\alpha_{n,i}$ represents the value of the normal incidence sound absorption coefficient measured for a chosen absorbent material at the i-th frequency, and $\widehat{\alpha}_{n,i}$ is the corresponding estimated value, according to Eq. (16).

Minimization of Eq. (17) implies that

$$\frac{\partial \epsilon}{\partial Q_p} = 2\sum_{i=1}^{N} (\alpha_{n,i} - \widehat{\alpha}_{n,i}) \frac{\partial \widehat{\alpha}_{n,i}}{\partial Q_p} = 0. \tag{18}$$

We observe that Eq. (18) is a nonlinear equation that requires a numerical solution (Lindfield, Penny, 1995; Press *et al.*, 1992). It is possible, therefore, to obtain Q_{pi} for each type of material under the conditions and limitations discussed above. The process would be as follows:

For two materials, 1 and 2, with different volumetric density and different thicknesses, made from fibres of same type (i.e, identical fibre diameter and density) the following equation must be verified

$$\frac{Q_{H1}}{Q_{H2}} = \frac{Q_{p1}}{Q_{p2}}. \tag{19}$$

Now, for two generic samples, i and $i+1$, we can define a new parameter, y_i, by means of

$$y_i = \frac{Q_{pi}}{Q_{pi+1}} - \frac{Q_{Hi}}{Q_{Hi+1}}, \tag{20}$$

which only depends on the fibre density ρ_f.

Therefore, we can obtain Q_{pi} and Q_{pi+1} by means of previous minimization process and ρ_{mi} and ρ_{mi+1} from a direct experimental measurement. Then, making $y_i = 0$ the equation can be solved and, consequently, the fibre density is determined. However, the process is not as simple, since Q_{Hi} presents convergence problems. To overcome this problem, Eq. (20) has been rewritten as

$$y_i = \frac{Q_{pi}}{Q_{pi+1}} - \frac{Q_{Hi}}{Q_{Hi+1}} = \frac{N_i}{D_i}, \tag{21}$$

where

$$\begin{aligned} N_i = {} & (Q_{pi+1}\rho_{mi} - Q_{pi}\rho_{mi+1})\rho_f^5 + (Q_{pi+1} - Q_{pi})\rho_{mi}\rho_{mi+1}\rho_f^4 \\ & + 10^4(2Q_{pi+1}\rho_{mi}\rho_{mi+1}^2 - \rho_{mi+1}^3 Q_{pi} - 2\rho_{mi+1}Q_{pi}\rho_{mi}^2 + \rho_{mi}^3 Q_{pi+1})\rho_f^3 \\ & + 10^4\left((Q_{pi} - 2Q_{pi+1})\rho_{mi+1}^3\rho_{mi} - (Q_{pi+1} - 2Q_{pi})\rho_{mi}^3\rho_{mi+1}\right)\rho_f^2 \\ & + 2\times 10^8\big((-Q_{pi}\rho_{mi+1}^3\rho_{mi}^2 + Q_{pi+1}\rho_{mi}^3\rho_{mi+1}^2)\rho_f \\ & + (Q_{pi}\rho_{mi+1}^3\rho_{mi}^3 - Q_{pi+1}\rho_{mi}^3\rho_{mi+1}^3)\big) \end{aligned}$$

and

$$\begin{aligned} D_i = {} & Q_{pi}\rho_{mi}\rho_f^5 + Q_{pi}\rho_{mi}\rho_{mi+1}\rho_f^4 + 10^4(2Q_{pi}\rho_{mi}\rho_{mi+1}^2 + \rho_{mi+1}^3 Q_{pi})\rho_f^3 \\ & - 10^4(Q_{pi}\rho_{mi}^3\rho_{mi+1} - 2Q_{pi}\rho_{mi+1}^3\rho_{mi})\rho_f^2 \\ & + 2\times 10^8(Q_{pi}\rho_{mi+1}^2\rho_{mi}^3\rho_f - Q_{pi}\rho_{mi+1}^3\rho_{mi}^3). \end{aligned}$$

For M samples, this function can be generalized as follows

$$y = \frac{1}{M-1}\sum_{i=1}^{M-1} y_i^2. \tag{22}$$

Solving for $y = 0$ by means of the minimization process described above, it can be obtained the fibre density ρ_f. Finally, the process finishes using Eqs. (3) and (12) to obtain porosity and average fibre diameter for each material.

3. Results

The experimental basis taken to validate the proposed method consists of two groups of materials, made of Kenaf (Ramis *et al.*, 2010) and Polyester (Garai, Pompoli, 2005). The values of density and thickness of the samples made of Kenaf and Polyester wool are shown in Tables 1 and 2, respectively. The prefix “k” and “S” have been used to denote the samples of Kenaf and Polyester, respectively.

Table 1. Bulk density and thickness of the Kenaf samples.

	e [mm]	ρ_m [kg/m^3]
k1	18	120.0
k2	22	80.0
k3	44	35.0
k4	18	120.0
k5	68	51.0
k6	41	45.0
k7	82	32.0

Table 2. Bulk density and thickness of the Polyester samples.

	e [mm]	ρ_m [kg/m^3]
S1	18	25.0
S2	22	24.6
S3	44	34.1
S4	18	58.0
S5	68	59.0

Figures 2 and 3 show the electron microscopy images of these two types of fibres. The values of fibre diameter for each sample of the materials have been obtained by digital image processing software, from the electron microscopy images of the samples. In this software, pixels are transformed into metric units with the purpose of obtaining the average diameter. The standard deviation has been determined as the square root of the variance. The measured average diameter of the Kenaf fibre was 78 μm, and for Polyester fibre, 32 μm. Therefore, according to Eq. (9) the Voronina model is still valid above a frequency of 100 Hz.

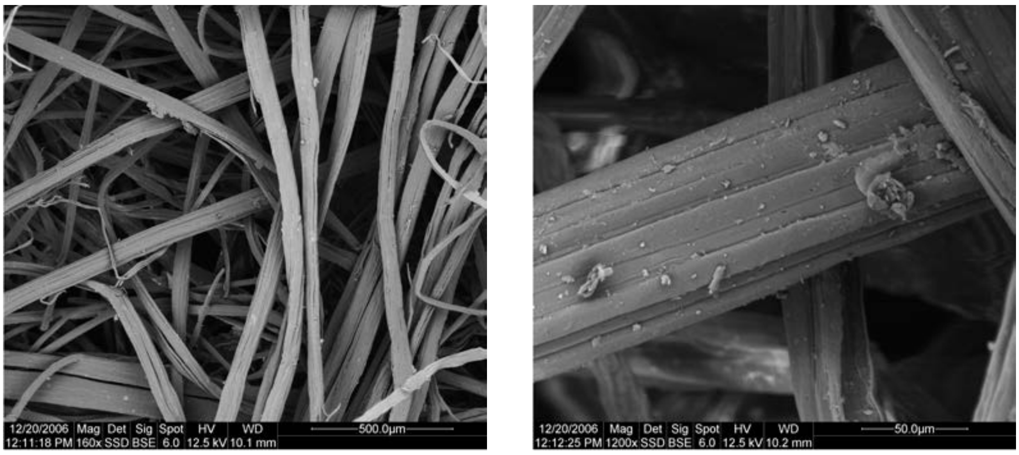

Fig. 2. Electron microscopy images of Kenaf wool.

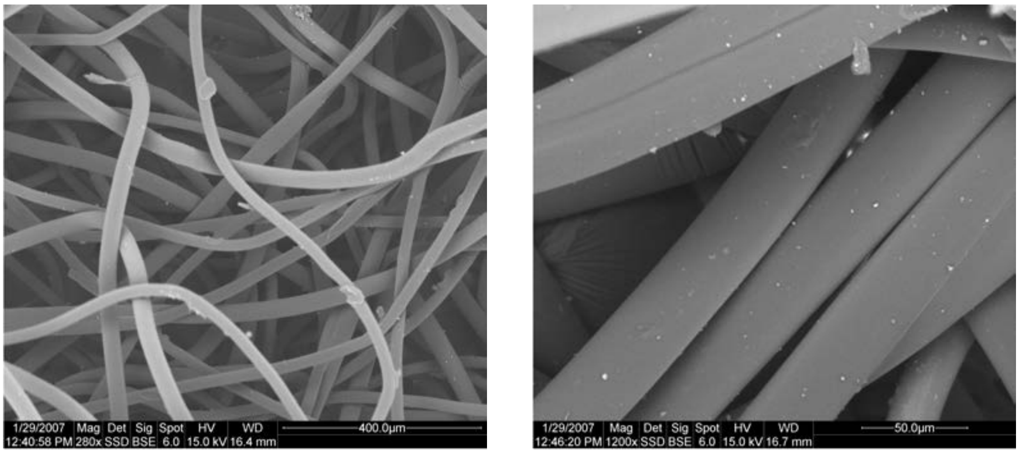

Fig. 3. Electron microscopy images of Polyester wool.

Several measurements of the normal incidence sound absorption coefficient α_n were made according to the ISO standard in the Acoustics Laboratory of the Polytechnic School of Gandia (EPSG) in Valencia. Figures 4 and 5 show the average results for the different samples made of Kenaf and Polyester fibre, respectively. Each sample was measured at least three times. In Fig. 4 we observe that increasing the thickness of the material, the low-frequency absorption is improved without significantly changing the high frequency characteristics. On the other hand, in Fig. 5 we observe that materials labeled as S4 and S5 do not follow this trend and they present similar values of sound absorption coefficient. This is because both materials have comparable values of flow resistance.

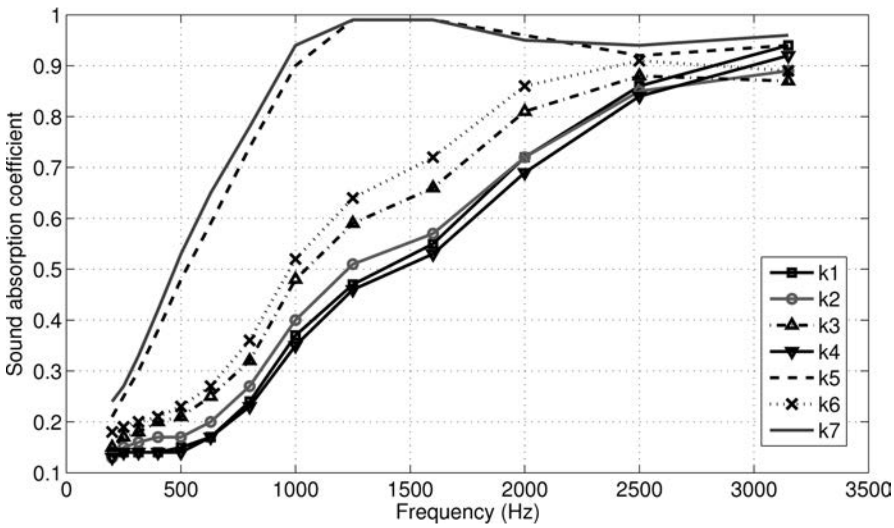

Fig. 4. Measured sound absorption coefficient of the Kenaf wool. k1 to k7 are the different samples of Kenaf.

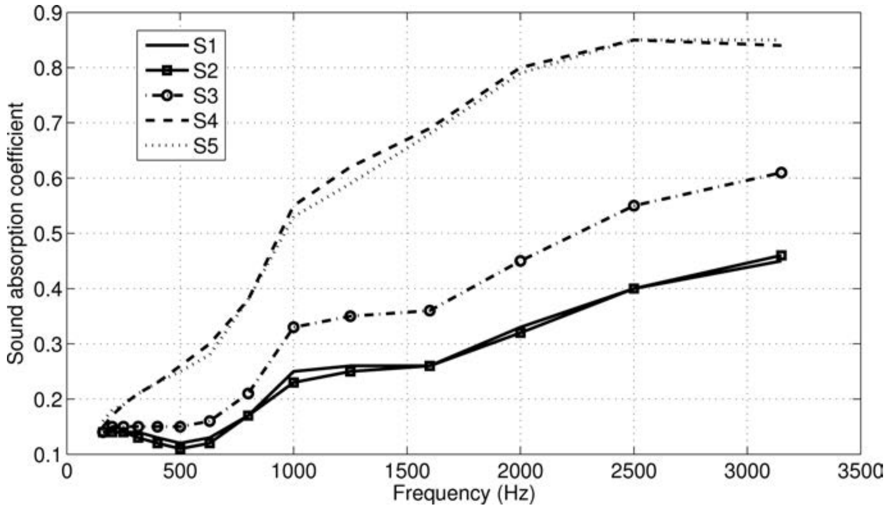

Fig. 5. Measured sound absorption coefficient of the Polyester wool. S1 to S5 are the different samples of Polyester.

Once the tests were done, the inversion process was performed. A Matlab© program was implemented in order to minimize Eq. (18) and obtain Q_p. The optimization process was performed using the Nelder-Mead simplex (direct search) method. Considering that $H \geq 0.5$ and $d \geq 10^{-6}$ m, the constraints are $Q_p < 600$ and $\rho_f \geq 2\rho_m$. The results are shown in Tables 3 and 4 for Kenaf and Polyester wool samples, respectively.

Table 3. Results for Kenaf fibre samples.

	Q_p	H	Q_H	d [μm]
k1	2.825	0.732	0.360	76.9
k2	1.657	0.822	0.215	79.1
k3	0.652	0.922	0.084	78.9
k4	2.795	0.732	0.360	78.9
k5	1.008	0.886	0.127	77.0
k6	0.847	0.900	0.111	79.8
k7	0.598	0.929	0.077	78.3

Table 4. Results for Polyester fibre samples.

	Q_p	H	Q_H	d [μm]
S1	0.324	0.985	0.018	33.9
S2	0.363	0.985	0.018	30.0
S3	0.399	0.979	0.023	35.5
S4	0.802	0.965	0.038	28.6
S5	0.772	0.964	0.039	30.3

Figure 6 provides four examples of the results for the minimization process. It is important to note that the errors resulting from the quadratic error function (17) are less than 0.01. The calculation is done within a few seconds only. All calculations converge toward the same solution starting with any initial seed.

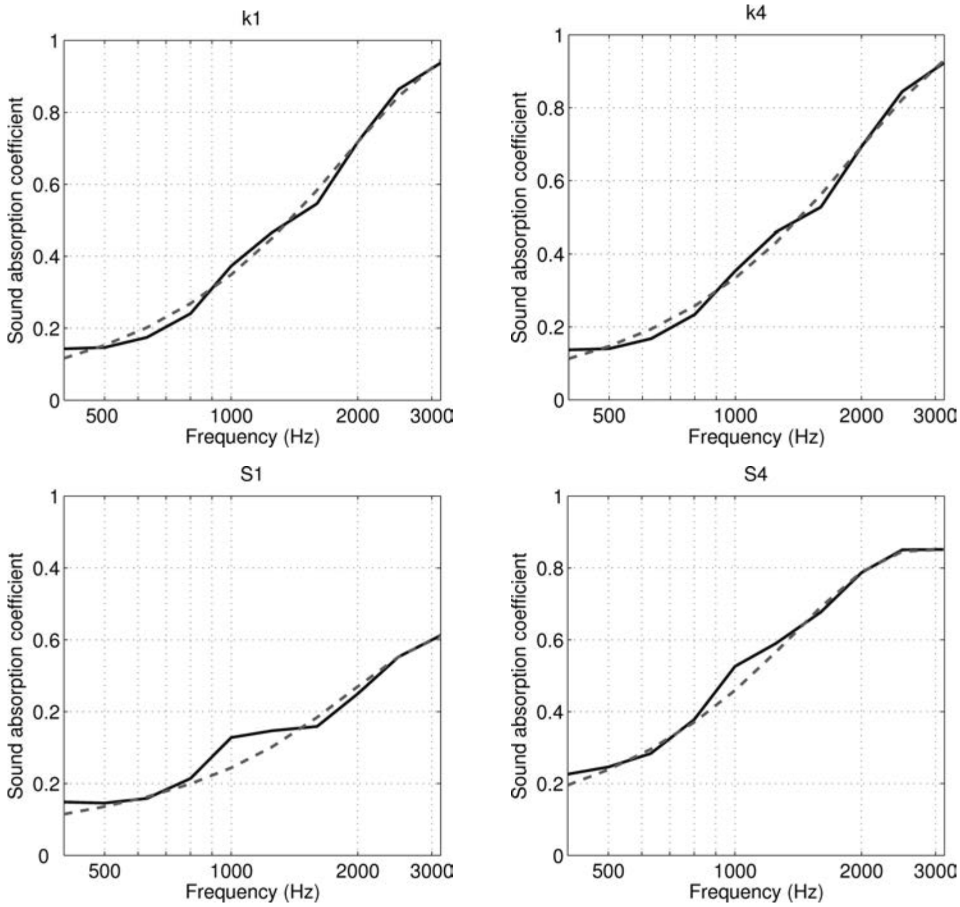

Fig. 6. Four representative examples of the minimization adjustment process (Kenaf: k1 and k4, Polyester: S1 and S4). Continuous line: measurement, dashed line: adjustment.

Finally, from the results of Q_p obtained for Kenaf, Eq. (22) is equated to zero. The Kenaf fibre density obtained is 448.5 kg/m^3. With this data, porosity and average fibre diameter is computed for each material in each case. The results are shown in Table 3. It results in a fibre average diameter of 78.6 µm, with a standard deviation of 0.9 µm. Analogous procedure is performed for Polyester fibre and the results are presented in Table 4. Now, fibre density of 1767.6 kg/m^3, average fibre diameter of 30.9 µm, and standard deviation of 2.9 µm are obtained. Figure 7 shows the corresponding quadratic errors as a function of the average fibre densities (ρ_f). It can be seen that this function is stable. In addition, we observe the presence of a single local minimum in the interval defined by the constraints. As the range of density values of material samples is increased this minimum becomes narrower.

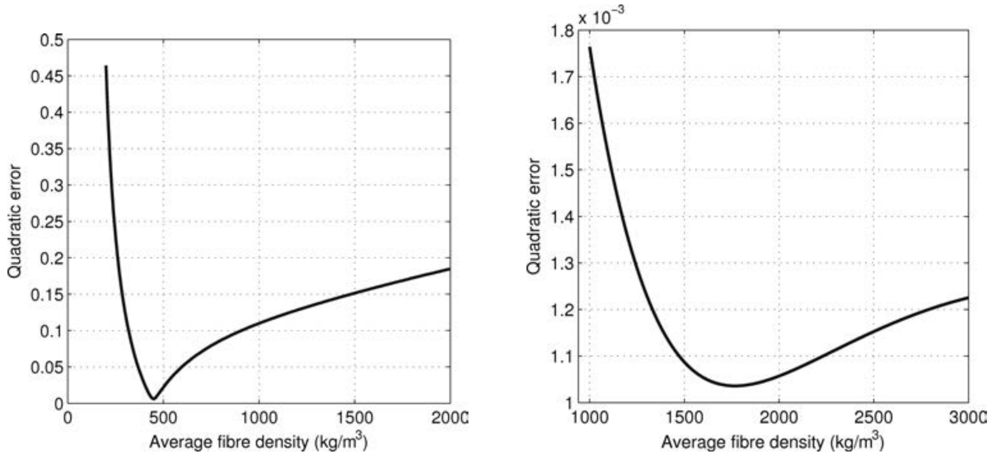

Fig. 7. Quadratic error function (Eq. (17)). Left: Kenaf fibre. Right: Polyester fibre.

4. Conclusions

An inverse method to obtain porosity, diameter and density that works for fibrous materials, meeting the requirements of the Voronina model, has been implemented. This model uses a minimum fibre diameter size and has high porosity requirements. The results obtained with the samples are consistent, since porosity values decrease as the density of material rises. Both the numerical model for inversion and the equation to obtain porosity have proved to be stable and convergent. The search for the structural characteristic converges to an unique value. In addition, this search does not depend on frequency, which simplifies the search for the minimum. The only precaution to be taken into account is that the material density must be measured precisely, because the process is sensitive to small variations of this parameter. Finally, it must be considered that the method is valid for high porosity materials, such that porosity is greater than 0.7.

Further studies are currently underway to extend this method to materials with thinner fibres and to cellular porous materials (depending on the mean pore diameter) so that this method may be evaluated under other conditions.

Acknowledgments

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