Empiric acoustic modeling of open-cell polyolefin foams

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ABSTRACT
Open-cell polyurethane (PU) foams are widely used in sound absorption applications. However, PU presents critical limitations, such as the toxicity of the fumes released when they are burnt, which makes necessary the search of potential substitutes to them. Open-cell polyolefin foams have emerged as potential alternative to open-cell PU foams. In this paper, the sound absorption properties of different materials developed from low-density polyethylene (LDPE) and ethylene vinyl acetate copolymer (EVA) are studied. Experimental measures have been carried out to determine the characteristic wave impedance, propagation constant and porosity of these materials. Modelling of the acoustic behavior has been done using different models.

Keywords: Open-cell foams, Porous material, Sound absorption, Model prediction
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1. INTRODUCTION

Porous materials are widely used as sound absorbing materials in noise control engineering. A porous absorbing material is a solid that contains cavities, channels or interstices so that the sound waves are able to enter through them. Based on their microscopic configurations porous absorbent materials can be classified as cellular, fibrous, or granular [1,2].

Starting in the late 1990s and the beginning of the 21st century, the benefits of using natural fibers as an alternative to synthetic ones have gradually emerged; they would provide high thermal and acoustic properties with a low impact on the environment and human health [3]. Over the years, researchers have conducted numerous studies to evaluate the acoustic and thermal properties of a multitude of natural fibers [4–11] and recycled materials [12–17]. They have made simulation models with these new materials [18–20].

This trend in the search of sustainable, recycled and recyclable materials, which are friendly both to the environmental and human health, is gaining increasingly greater force [21]. Currently, the HORIZON2020 program is up and running [22], and is the most ambitious research and innovation program set up by the European Union. This program funds research and innovation projects in various subject areas in the European context and, in particular, its Action 5 poses different plans to be put into action. One of them refers to “enabling the transition towards a green economy and society through eco-innovation”, by reinforcing innovative sustainable products, among others. This has also implied the necessity to face the implementation of models which could make the prediction of the acoustic behavior of these materials easier [23].

In recent years, different macroscopic empirical models to predict the sound absorption of porous absorbent materials have been reported. Although there are restrictions on the applicability of them, they usually give reasonable estimations across a wide frequency range. The most common materials that have been studied through these models have been basalt and rock wool and glass fiber.

One of the most used models has been the one proposed for fibrous absorbent materials by Delany and Bazley [24] based in a large number of impedance tube measurements and curve fitting. This model provides good estimations for characteristic impedance and propagation constant for frequencies above 250 Hz, but prediction has significant errors at lower frequencies. Further updates and improvements were recommended by Miki [25,26] and later by Mechel and Grundmann [27]. Other empirical model was suggested for the case of foams by Dunn and Davern [28]. An important body of research has been reported by Voronina [29–33] aimed to characterize sound absorbing materials from physical parameters such as tortuosity and structure factor associated either to the fibers or pores layout.

In this context, some standards such as UNE-EN 12354:2003 [34] (the European standard used in the Building Technical Code in Spain), recommend the use of formulas
for the prediction of the sound absorption of materials. The standard enforces the use of the Delany and Bazley model in the case of materials made up of fibers whereas the model by Dunn and Davern is used for foam materials. These models are based on the determination of eight real constants $C_i$ that best fit a set of equations for the case of a porous material from the measured flow resistivity data [24].

In this work, the sound absorption properties of different materials developed from low-density polyethylene (LDPE) and ethylene vinyl acetate copolymer (EVA) are studied. These foams are presented as an alternative to PU foams since are more environmentally friendly due to the toxicity degree of the PU foams at the time of being recycled.

The acoustic behavior of the open-cell polyolefin foams has been modeled from two different points of view. On the one hand, air flow resistivity has been used as a simple parameter to describe the properties of the foam material, following the recommendations made by Dunn and Davern [28]. On the other hand, the porosity and the average pore diameter of the foams have been considered as two acoustic parameters to follow the procedure described by Voronina for highly porous materials [13]. In both cases, the characteristic wave impedance and propagation constant are the main values used to predict the characteristics of the material.

2. THEORETICAL BACKGROUND

2.1 Dunn and Davern Model

The semi-empirical model presented by Dunn & Davern [28] is used to describe the acoustic behavior of fibrous materials, according to a few no intrinsic physical parameters. Thus, we have in the equation the smallest possible margin of error. It comes to finding the coefficients $C_i$ $(i = 1...8)$ that best fit the following equations for the case of material we are dealing with:

$$\alpha = \left(\frac{2\pi f}{c_0}\right) \left[C_5 \left(\frac{\rho_0 f}{r}\right)^{-C_6}\right]$$  

$$\beta = \left(\frac{2\pi f}{c_0}\right) \left[1 + C_7 \left(\frac{\rho_0 f}{r}\right)^{-C_8}\right]$$  

$$Z_R = \rho_0 c_0 \left[1 + C_1 \left(\frac{\rho_0 f}{r}\right)^{-C_2}\right]$$  

$$Z_I = -\rho_0 c_0 \left[C_3 \left(\frac{\rho_0 f}{r}\right)^{-C_4}\right]$$

where $\alpha$ and $\beta$ are the real and imaginary parts of the propagation constant, $Z_R$ and $Z_I$ are the real and imaginary parts of the specific acoustic impedance, $r$ is the airflow resistivity $(N \times s/m^4)$, $f$ is the frequency (Hz), $\rho_0$ is the air density ($\approx 1.2 \text{ kg/m}^3$) and $c_0$ is the speed of sound in the air ($\approx 343 \text{ m/s}$).
Moreover, to obtain the normal incidence sound absorption coefficient through the propagation constant and the specific acoustic impedance, Equation 5 is used [35].

$$\alpha_n = \frac{4 \, Z_{lR} \rho_0 c_0}{|Z_l| + 2 \rho_0 c_0 Z_{lR} + (\rho_0 c_0)^2}$$

(5)

Being \(l\) the thickness of the sample and the expression for the closing impedance:

$$Z_l = (Z_R + j Z_I) [\coth(\alpha + j \beta) \times l]$$

(6)

### 2.2 Voronina model for porous materials

Sound propagation through a homogeneous and isotropic material in the frequency domain is determined by two complex values, i.e. the characteristic propagation constant \((\Gamma = \alpha + j \beta)\) and the characteristic wave impedance \((Z = R + j X)\), where \(\alpha\), \(\beta\), \(R\), and \(X\) are real functions of frequency.

Due to its simplicity, in this work it was also decided to use the Voronina [30–32] model, 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 [1]. It can be expressed as a function of the volumetric densities of the material, \(\rho_m\), and the fiber, \(\rho_f\), as:

$$H = 1 - \frac{\rho_m}{\rho_f}$$

(7)

The Voronina model uses analytical functions that vary with the porosity of the material, the frequency, and the average pore diameter. A quantitative estimation of energy losses in the porous medium is given by the structural characteristic, \(Q\), defined as:

$$Q = \frac{1 - H}{\sqrt{H \, D}} \sqrt{\frac{200 \mu}{k \rho_0 c_0}}$$

(8)

where \(\mu = 1.85 \cdot 10^{-5} \text{ Pa} \cdot \text{s}\) is the dynamic viscosity coefficient of air and \(D\) is the pore diameter.

In the case where \(Q < 1\), the characteristic wave impedance and the propagation constant are obtained from the structural characteristic by means of the simplified equations [32]:

$$Z = (1 + Q) - j \frac{Q}{2}$$

(9)

$$\Gamma = kQ + j k (1 + Q (1 + B))$$

(10)
where \( k \) is the free field wavenumber (\( 2\pi f / c \)) and \( B \) is a parameter that depends on the structural characteristic \([31]\). When \( Q > 1 \), the equations are now given by:

\[
Z = (1 + Q) - j \frac{Q}{2 + Q/(1 + \sqrt{Q})^2} \tag{11}
\]

\[
\Gamma = \frac{2kQ}{2 + Q/(1 + \sqrt{Q})^2} + jk(1 + Q(1 + B)) \tag{12}
\]

Therefore, if porosity and average pore diameter are known for a material then the structural characteristic and, consequently, the characteristic wave impedance and propagation constant can be calculated according to Equations (9) to (12).

3. RESULTS

3.1 Experimental results

In order to determine the real and imaginary parts of the propagation constant and the normalized characteristic impedance of the material it is necessary to measure both the normal incidence absorption coefficient and the flow resistivity of the material. The normal incidence sound absorption coefficient is experimentally obtained using the transfer-function method, which is comprehensively described in the ISO standard \([36]\).

On the other hand, the flow resistivity of the material has been determined in the laboratory through the Ingard and Dear \([37]\) method, which is a good alternative to the ISO standard \([38]\). Figure I shows the experimental setup used for the measurements.

![Figure 1. Experimental measurement of the polyolefin foam samples. Left: Measurement of sound absorption coefficient, Right: Measurement of flow resistance using the Ingard and Dear method.](image-url)
Table 1 shows the values of the physical parameters (thickness, density, flow resistivity and porosity) of the open-cell polyolefin foams. Porosity values have been obtained with a porosimeter built based on the work of Champoux, described in [39]. All the details related to these measurements can be found in [40].

Figure 2. Built porosimeter prototype

Table 1. Physical parameters values of the open-cell polyolefin foams samples

<table>
<thead>
<tr>
<th>Material</th>
<th>Bulk Density (kg/m³)</th>
<th>Thickness (cm)</th>
<th>Flow resistivity (kPas/m²)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDPE Low Tortuosity (LDPE-LT)</td>
<td>16.60</td>
<td>2.85</td>
<td>14.3 – 16.1</td>
<td>0.81</td>
</tr>
<tr>
<td>LDPE High Tortuosity (LDPE-HT)</td>
<td>22.40</td>
<td>2.99</td>
<td>13.2 – 14.4</td>
<td>0.94</td>
</tr>
<tr>
<td>EVA Low Tortuosity (EVA-LT)</td>
<td>25.20</td>
<td>3.21</td>
<td>15.0 – 15.4</td>
<td>0.77</td>
</tr>
<tr>
<td>EVA High Tortuosity (EVA-HT)</td>
<td>24.30</td>
<td>3.18</td>
<td>14.1 – 15.3</td>
<td>0.93</td>
</tr>
</tbody>
</table>

The cell diameter of the foams was estimated using X-ray tomography. The set-up consisted of a micro-focus cone beam X-ray source L10101 from Hamamatsu (Voltage: 20-100 kV, current: 0-200 μA) with a maximum output power of 20 W and a flat panel detector C7940DK-02, also from Hamamatsu. Once the projections were acquired, the reconstruction process of the tomogram was performed using Octopus reconstruction package. The cell diameter of the foams present high deviations, due to the lack of homogeneity of these foams. It has been considered the average diameter value for each foam type as the maximum value of a normal distribution. These values are presented in Table 2 and Figure 3.
Table 2. Cell diameter of the foams

<table>
<thead>
<tr>
<th>Material</th>
<th>Diameter (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDPE Low Tortuosity (LDPE-LT)</td>
<td>118</td>
</tr>
<tr>
<td>LDPE High Tortuosity (LDPE-HT)</td>
<td>327</td>
</tr>
<tr>
<td>EVA Low Tortuosity (EVA-LT)</td>
<td>223</td>
</tr>
<tr>
<td>EVA High Tortuosity (EVA-HT)</td>
<td>334</td>
</tr>
</tbody>
</table>

![Figure 3. Cell diameter distribution of the foams](image)

3.1 Numerical results

The constants that best fit the measured sound absorption coefficient of the open-cell polyolefin foam samples were determined by an iterative method based on a minimization of a quadratic error function. Several values proposed by different authors have been used as initial values (input values). Table 3 shows the values of the constants proposed by Dunn & Davern for fully reticulated polyurethane foam [28] and the values obtained from the minimization process for the each foam type analyzed in this work through the measured flow resistivity.

Table 3. Coefficient values

<table>
<thead>
<tr>
<th>Model</th>
<th>C₁</th>
<th>C₂</th>
<th>C₃</th>
<th>C₄</th>
<th>C₅</th>
<th>C₆</th>
<th>C₇</th>
<th>C₈</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dunn &amp; Davern</td>
<td>0.114</td>
<td>0.369</td>
<td>0.090</td>
<td>0.758</td>
<td>0.168</td>
<td>0.715</td>
<td>0.136</td>
<td>0.491</td>
</tr>
<tr>
<td>EVA-HT</td>
<td>0.079</td>
<td>0.901</td>
<td>0.070</td>
<td>0.763</td>
<td>0.184</td>
<td>0.039</td>
<td>0.121</td>
<td>0.812</td>
</tr>
<tr>
<td>Dunn &amp; Davern</td>
<td>0.056</td>
<td>0.916</td>
<td>0.013</td>
<td>0.904</td>
<td>0.243</td>
<td>-0.378</td>
<td>0.109</td>
<td>0.872</td>
</tr>
<tr>
<td>EVA-LT</td>
<td>0.444</td>
<td>10.96</td>
<td>0.078</td>
<td>7.111</td>
<td>0.038</td>
<td>-0.485</td>
<td>1.093</td>
<td>13.657</td>
</tr>
<tr>
<td>Dunn &amp; Davern</td>
<td>0.055</td>
<td>0.625</td>
<td>0.068</td>
<td>0.776</td>
<td>0.288</td>
<td>-0.547</td>
<td>0.089</td>
<td>0.742</td>
</tr>
</tbody>
</table>
Figure 4 shows a comparison between the experimental sound absorption coefficient values for the different open-cell polyolefin foam types as a function of frequency and those determined from the three models compared in this work. Frequency (Hz) and sound absorption coefficient are presented in the abscissas and ordinates axes respectively.

Figure 4. Dunn & Davern generic model vs custom model.

In addition, the results of normal incidence sound absorption coefficient predicted by the Voronina model are presented in Figure 5.
For measuring the dispersion, the mean deviation between the measured and calculated values of sound absorption coefficient for the three models was calculated. Results are presented in Table 4. Dispersion of the different models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Dunn &amp; Davern Dispersion</th>
<th>Custom Dunn &amp; Davern Dispersion</th>
<th>Voronina Dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVA-HT</td>
<td>0.2477</td>
<td>0.2022</td>
<td>0.2081</td>
</tr>
<tr>
<td>EVA-LT</td>
<td>0.3154</td>
<td>0.3587</td>
<td>0.3934</td>
</tr>
<tr>
<td>LDPE-HT</td>
<td>0.1447</td>
<td>0.1396</td>
<td>0.1553</td>
</tr>
<tr>
<td>LDPE-LT</td>
<td>0.4054</td>
<td>0.2713</td>
<td>0.3995</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS
An experimental investigation has been done to determine the characteristic wave impedance and propagation constant of open-cell polyolefin foams. These materials have emerged as a potential alternative to open-cell PU foams. PU presents critical limitations, such as the toxicity of the fumes released when they are burnt, which makes necessary the search of potential substitutes to them.

Although the samples used for the experimental tests present absorption coefficient values typical of an absorbent material, all of them present an absorption peak difficult to model by means of classic empirical models.

When modeling the propagation of sound within the foam it is observed that the model proposed by Dunn and Davern presents inaccurate predictions of the sound
absorption coefficient. In particular, the predicted sound absorption coefficient is lower than its measured value in all the frequency range. Predicted values by Dunn and Davern model do not either show that maximum absorption peak under no circumstances. Custom parameters for each foam type (EVA-HT, EVA-LT, LDPE-HY and LDPE-LT) have been obtained by means of an adjusted model based on Dunn and Davern model. In this case, absorption values are closer to experimental values, but the absorption peaks present in experimental measurements are neither obtained.

On the other hand, the use of the Voroninina model after determining the average pore diameter gives good prediction of the sound absorption of the low tortuosity foams (EVA-LT and LDPE-LT) but results for the high tortuosity foams are not as good.

The obtained results show the necessity of finding a new model that take into account the tortuosity parameter in the absorption coefficient analysis. The authors consider that a detailed evaluation of these foams absorption based on non-acoustic parameters, as the carried out by Naoki Kino [41] based on Johnson–Champoux–Allard (JCA) model.

5. REFERENCES


24. Delany, M. E.; Bazley, E. N. Acoustical Properties of Fibrous Absorbent


40. del Rey, R.; Alba, J.; Arenas, J. P. Validación de Un Dispositivo Para La Medida de Porosidad. In *FIA 2018. XI Congreso Iberoamericano de Acústica; X Congreso Iberico de Acústica; 49° Congreso Español de Acústica -TECNIAUSTICA’18*; 2018.