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Effect of non-acoustic properties on the sound absorption of polyurethane foams

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K E Y W O R D S

Porous media

Polyurethane

Non-acoustic properties

Absorption coefficient

A B S T R A C T

In this paper the influence of non-acoustic properties on the sound absorption coefficient of polyurethane foams as a porous medium is investigated. Biot's equations with transfer matrix method, as the solution approach are employed to evaluate the sound absorption coefficient of selected polyurethane foams. The major issue is the dependency of non-acoustic properties on each other which makes difficulties to examine the effect of parameters individually. Some facts from the results of previous works are used in order to overcome this prominent obstacle. The results show that increasing the porosity doesn't have a great influence on the sound absorption coefficient and only for highly porous foams, raising porosity decreases the sound absorption performance. The increase of air flow resistivity up to an optimized value, intensifies the absorption capability. Furthermore, for partially reticulated (partially open cell) foams, the increase of tortuosity improves the sound absorption efficiency at lower frequencies.

1. Introduction

Porous materials are a combination of two distinct phases, fluid phase (usually air) and solid phase (frame). These kinds of new interesting materials have a great application in acoustic science, especially for sound absorbing goals. Interaction of the fluid and solid phases leads to further attenuation of wave's energy in comparison to a mere solid or fluid medium.

Porous media whose solid phase is elastic and the fluid phase is viscous are called poroelastic. For the first time, Biot [1-3] introduced the governing equations of sound propagation in a poroelastic medium. The equations are written with the help of non-acoustic properties [4, 5].

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One solution method of Biot's equations, which is called transfer matrix method, has wide applications in the optimisation of absorbent layers [6, 7]. Among several kinds of porous materials including rocks, soils and man-made materials such as foams and ceramics, polyurethane foam is very common in sound absorbing applications. Researchers have done several works on polyurethane foams and other porous materials to improve their sound absorption efficiency. To this end, having a whole understanding of the effect of non-acoustic parameters on the sound absorption is the integral part of any research.

Doutres et al. [8] established some semi-empirical relations between microstructure and non-acoustic properties of polyurethane foam. In two recent articles, they worked on the accuracy and simplicity of the relations [9, 10]. Bies and Hansen [11] discussed the role of flow resistance for fibrous and foamed products in three acoustical applications including attenuation of sound propagating in ducts. In a more recent work, Cuiyun et al. [12] studied acoustical properties of a ceramic porous material and explained the effect of thickness and porosity on the sound absorption performance. However, to our knowledge, the direct effect of non-acoustic parameters on the sound absorption coefficient of polyurethane foams has not been discussed yet.

In this work, after a brief presentation of non-acoustic parameters, governing equations and solution methods (Sections 2-4), the direct influence of those parameters on the sound absorption coefficient of polyurethane foam samples is investigated (Section 5). It is the complement key to the optimization of the foaming process.

2. Non-acoustic properties of porous media

Firstly it is important to review non-acoustic properties of a porous medium which are governing parameters for the propagation and absorption of sound within porous materials. They are prerequisite for modelling of sound propagation in porous material.

Porosity: It is the volume fraction of a porous material occupied by the fluid phase. If V^T is the total volume of the porous material and volumes of the solid and fluid phases are indicated by V^s and V^f respectively, then it concludes $V^T = V^s + V^f$. The porosity (ϕ) of the material is defined as $\phi = \frac{V^f}{V^T}$ [4]. For highly porous material, porosity can be stated as [8],

$$\phi = 1 - \frac{\rho_s}{\rho_m} \tag{1}$$

where ρ_s is the solid phase or frame density and ρ_m is the solid phase material density.

Air flow resistivity: It is the resistance of a porous material to an air flow. If a steady air stream of mean flow rate per unit area V is passed through a porous layer of thickness d and causes a pressure gradient ΔP between the surfaces of the layer, then the air flow resistivity is $\sigma = \frac{\Delta P}{Vd}$ [4].

Tortuosity: The ratio of the real distance to the apparent way which the air has to pass to move from one side to another side of the sample is called tortuosity. A method for tortuosity measurement exists which can only be used in the case of non-conductive frame as it commonly happens in porous materials. In the mentioned method, the porous material is saturated with a conducting fluid. Then the resistivity of the saturated material is measured. Let r_c and r_f be the measured resistances of the saturated material and the fluid respectively. The tortuosity is then given by $\alpha_\infty = \phi \frac{r_c}{r_f}$ [4].

Viscous characteristic length: Johnson et al. [5] have defined a characteristic dimension which is called viscous characteristic length Λ, and includes the effect of viscosity at high frequencies. It has been noted by Johnson et al. that the viscous characteristic length is related to other properties by,

$$\Lambda = \frac{1}{c}\left(\frac{8\eta\alpha_\infty}{\sigma\phi}\right)^{1/2} \tag{2}$$

where η is the air viscosity and c is a constant.

Thermal characteristic length: There is another parameter that introduces the heat transfer which occurs between two phases at high-frequency range called thermal characteristic length Λ' and is given by [4],

$$\Lambda' = \frac{2\int_V dV}{\int_A dA} = \frac{2V}{A} \tag{3}$$

The integral in the numerator is performed over the pore surfaces A in the elementary representative volume and the integral in the denominator is performed over the volume V of the pore. A similar relation can relate Λ' to other parameters [4];

$$\Lambda' = \frac{1}{c'}\left(\frac{8\eta\alpha_\infty}{\sigma\phi}\right)^{1/2} \tag{4}$$

where c' is also a constant. Two characteristic lengths Λ and Λ' only depend on the geometry of the frame, therefore, constants c and c' are such as well and have a value in the range [0.3 , 3], for all types of foam with the consideration that $c' \leq c$ [4].

3. Governing equations of sound propagation in porous media (Biot equations)

Propagation of waves in porous media is expressed via dynamic equations known as Biot equations. In a series of papers [1-3], Biot developed the theory of dynamic poroelasticity (presently known as the Biot theory) which gives a comprehensive description of the mechanical behavior of a poroelastic medium. Biot equations of poroelasticity are derived through a Lagrangian approach. One of the key findings of this theory is that in poroelastic media, there exist three types of waves: a shear or transverse wave and two types of longitudinal or compressional waves. In the present work, Biot equations are used as reference [7] for calculation of sound absorption coefficient. For detail information, readers are referred to [7]. As a summary, equations of propagation of sound in elastic porous media are as follows.

$$\begin{aligned} \nabla.\boldsymbol{\sigma}^s &= [\tilde{\rho}_{11}]\ddot{\boldsymbol{u}}^s + [\tilde{\rho}_{12}]\ddot{\boldsymbol{u}}^f \\ \nabla.\boldsymbol{\sigma}^f &= [\tilde{\rho}_{12}]\ddot{\boldsymbol{u}}^s + [\tilde{\rho}_{22}]\ddot{\boldsymbol{u}}^f \end{aligned} \tag{5}$$

where $\boldsymbol{\sigma}$ displays the stress tensor and $\boldsymbol{u}$ is the displacement tensor. Signs f and s show the fluid and solid phases respectively. $[\tilde{\rho}_{ij}]$ $(i,j=1,2)$ are tensors of second order which are called Biot densities. These quantities are evaluated based on properties as,

$$\begin{aligned}[\tilde{\rho}_{12}] &= \phi\rho_f([I]-[\tilde{\alpha}])\\ [\tilde{\rho}_{22}] &= \phi\rho_f([I]-[\tilde{\rho}_{12}])\\ [\tilde{\rho}_{11}] &= (1-\phi)\rho_s[I]-[\tilde{\rho}_{12}]\end{aligned} \tag{6}$$

where ϕ is porosity and $[\tilde{\alpha}]$ reperesents dynamic tortuosity [7] which is defined based on non-acoustic properties. ρ_f and ρ_s are the densities of the fluid and solid phases respectively.

4. Solution method

For solving the Biot's equations and calculating the acoustical properties, different methods can be implemented. Not only numerical methods such as finite element can be used, but also analytical methods like the transfer matrix method can be applied. In this work, the transfer matrix method (TMM) is employed to compute the absorption coefficient of a porous layer as has been applied in [7]. Although in the TMM method the lateral dimensions of the porous layer are assumed to be infinite, for comparison purposes it is the best method which can be chosen on account of its simplicity.

Solving the Biot's equations using the transfer matrix method for a porous layer gives the acoustical parameters like incident and reflected pressure amplitudes. Then reflection coefficient (R) is defined as $R=p'/p$ where p' and p are the amplitudes of reflected and radiated waves respectively. Ultimately, the absorption coefficient is evaluated based on the reflection coefficient.

$$\alpha = 1-|R|^2 \tag{7}$$

Absorption coefficient determines the amount of the absorbed energy of radiated wave by the porous media. It is the main acoustic property to examine the efficiency of absorbent materials.

5. Influence of non-acoustic properties of porous media on the sound absorption coefficient

The aim of this section is to investigate the effect of each non-acoustic property of a porous medium on its sound absorption coefficient. To this end, Biot's equations have been solved for one layer of polyurethane foam sample using the transfer matrix method as elaborated in Section 4. A MATLAB code is written to calculate the sound absorption coefficient in the frequency range of 1 *Hz* to 6300 *Hz*.

In order to apply governing equations, eleven samples of polyurethane foam from reference [6] are considered in Table 1 where the Young's modulus and Poisson's ratio of all samples are E=144000 *Pa* and υ= 0.3 respectively.

The eleven samples are divided into three groups with constant solid phase densities. The first group is with ρ_s= 856 kg/m^3, the second with ρ_s= 1285 kg/m^3 and the third with ρ_s= 2570 kg/m^3 categorized in the right column of Table 1.

Polyurethane foam has a cellular structure. Some of these cells are connected to each other within which air can flow freely. On the other hand, there are some membranes that can close the cells or prevent them to be directly connected, accordingly, obstruct the sound waves to propagate straightly. The former is called open pore content and the latter, closed pore content. Reticulation rate (R_W) determines the open pore content of a polyurethane foam. A foam with R_W=100% is known as *fully reticulated* and one with R_W<100% is called *partially reticulated*. These two terms will be used in the following.

Table 1. Non-acoustical properties of eleven samples of polyurethane (PU) foam [6].

Foam Number	ϕ	σ $(\mathrm{N.s/m^4})$	α_∞	Λ $(\mu\mathrm{m})$	Λ' $(\mu\mathrm{m})$	ρ $(\mathrm{kg/m^3})$	Group number
1	0.97	600	1.06	420	600	856	I
2	0.97	900	1.07	400	520	856	
3	0.97	1300	1.07	300	490	856	
4	0.97	3800	1.07	200	220	856	
5	0.98	2600	1.07	210	380	1285	II
6	0.98	10000	2.3	60	310	1285	
7	0.98	19000	1.7	20	270	1285	
8	0.99	1000	1.07	350	600	2570	III
9	0.99	1400	1.05	290	500	2570	
10	0.99	1700	1.04	290	490	2570	
11	0.99	1900	1.04	260	420	2570	

5.1. Basic facts

In the following, non-acoustic properties of a sample foam are changed and their effect on the sound absorption coefficient will be shown. Since there is a correlation between the properties of a porous medium, changing one of them results in variation of others. Therefore, some outcomes of previous works have been considered here as basic facts that make it possible to investigate the effect of so-called parameters on the sound absorption. These facts have been adopted from reference [8] as follows:

(a) The porosity of both fully reticulated and partially reticulated foams is independent of the cell size. It is only a function of solid material and frame densities (Eq. 1) as it is evident from the values of porosity in Table 1.

(b) For fully reticulated foams, tortuosity is independent of cell size. As shown in Table 1, the tortuosity of groups I and III is roughly unchanged while the airflow resistivity and characteristic lengths are changing (because of different cell size for each sample). So these two groups are fully reticulated and the cell sizes vary from one sample to another. It should be noted that higher flow resistivity and lower characteristic lengths show smaller cell size.

(c) For partially reticulated foams, presence of cell membranes cause airflow resistivity, tortuosity and the ratio of thermal to viscous characteristic length to increase, but it decreases these two characteristic lengths in comparison with a fully reticulated sample. Therefore samples of group II in Table 1 which their values illustrate the mentioned phenomena are partially reticulated.

5.2. Effect of porosity on the sound absorption coefficient

Based on point (a) of Section 5.1 and values of Table 1, porosity depends only on the solid phase and solid material densities. For each group of Table 1, the value of solid material density ρ_m has been calculated from Eq. (1) based on the values of ρ_s and ϕ. Then it is assumed that porosity varies in a narrow reasonable range and for each value of porosity, corresponding solid phase density is calculated using a revised form of Eq. (1) as $\rho_s = (1-\phi)\rho_m$. From a foaming process point of view, it is possible to change solid phase density and porosity while other parameters are constant. Three samples of Table 1 from different groups (sample 4 of group I, sample 6 of group II and sample 10 of group III) are picked here. The porosity changes in the range 0.95< ϕ <0.99. Figures 1-3 display the absorption coefficient of three selected samples for assumed porosities. Thickness of all samples is supposed to be 5 *cm*.

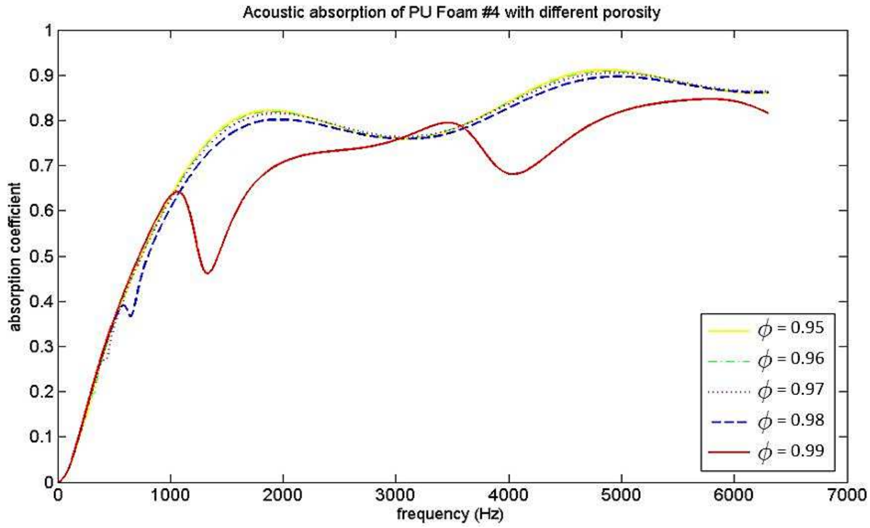

Fig. 1. Sound absorption coefficient of PU Foam #4 for different values of porosity

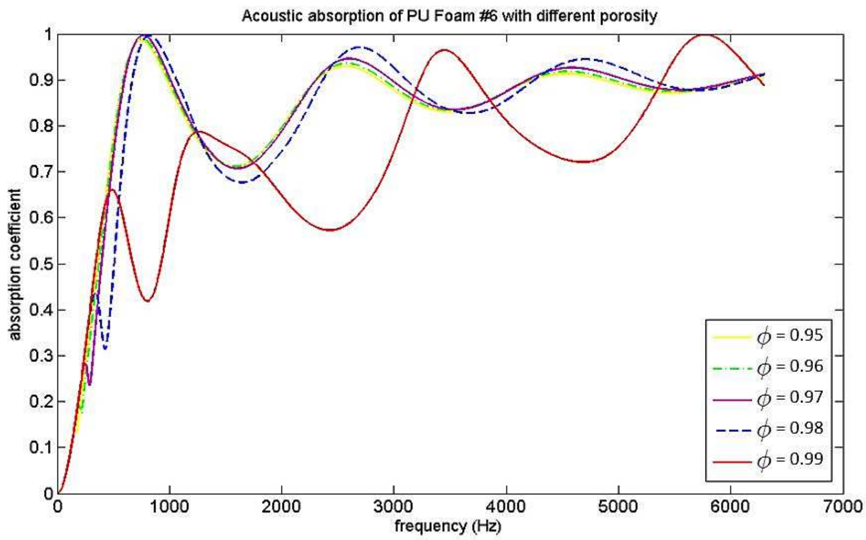

Fig. 2. Sound absorption coefficient of PU Foam #6 for different values of porosity

According to Fig. 1-3, in the case of fully reticulated foams (Fig. 1, 3), the increase of porosity does not have any considerable effect on the absorption coefficient. Only for some kinds (Fig. 1), after a special value of porosity, an irregular decrease of sound absorption is observed. For partially reticulated foam (Fig. 2) the effect of porosity is different. A slight increase of frequency at which sound absorption reaches its maximum is observed with more fluctuation of graph especially for frequencies greater than 1000 Hz. After some specific values of porosity, these observations are more considerable; also the first maximum of sound absorption is significantly decreased.

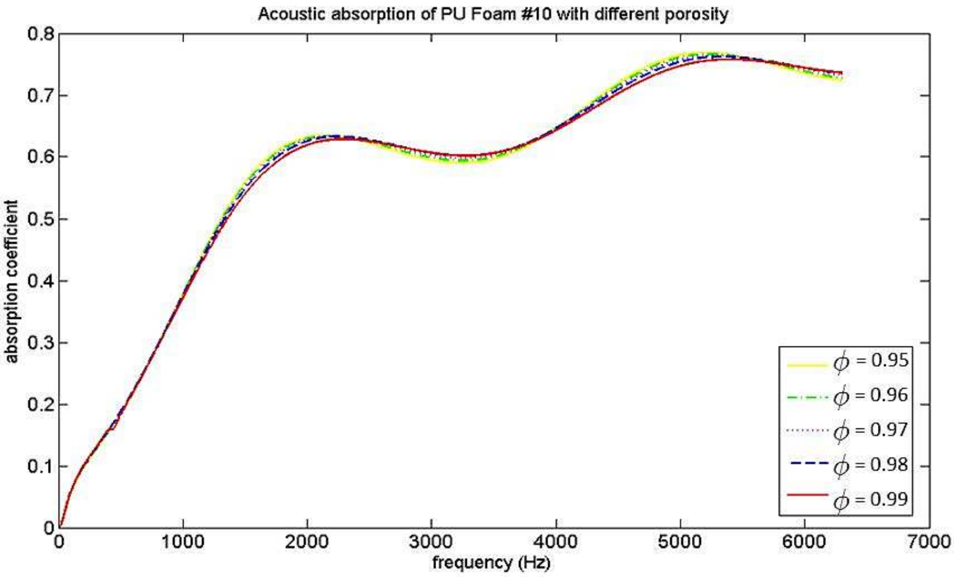

Fig. 3. Sound absorption coefficient of PU Foam #10 for different values of porosity

5.3. Effect of air flow resistivity and characteristic lengths on the sound absorption coefficient

According to Table 1 and points (b) and (c) of Section 5.1, air flow resistivity and characteristic lengths are completely dependent. To change these three properties coherently, Eqs. (2) and (4) of Section 2 are used. As stated before, constants c and c' only depend on the foam microstructure and vary in the range [0.3, 3]. Air flow resistivity is assumed to change in an acceptable range related to each sample compatible with the values of Table 1. At first, for each sample, values of c and c' are calculated based on real values of parameters using the mentioned equations. Since the calculated c and c' for different samples of similar groups are close to each other, it is reasonable to use an average value of c and c' for each group of Table 1. Then, these average values are used in Eqs. (2) and (4) to evaluate the characteristic lengths based on the new value of flow resistivity. Finally the sound absorption coefficient is computed in terms of new set of parameters. For group I, the average values of constants are c_{avg}=1.066 and c'_{avg}=0.827. Fig. 4 shows the result with air flow resistivity in the range of 500$<\sigma<$4500.

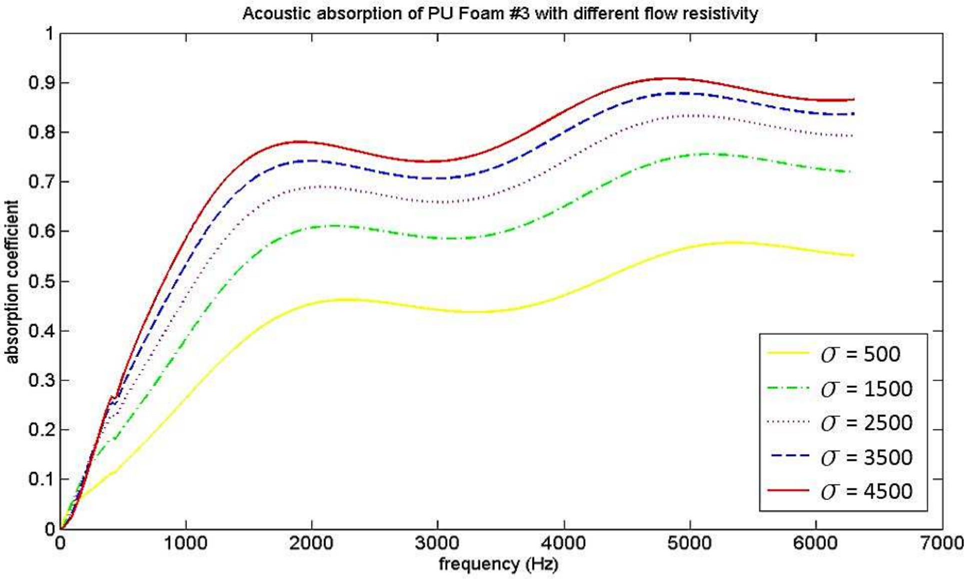

Fig. 4. Sound absorption coefficient of PU foam group I for different values of $\boldsymbol{\sigma}$, $\boldsymbol{\Lambda}$ and $\boldsymbol{\Lambda'}$

For group II, the average values are c_{avg}=2.144 and c'_{avg}=0.628. Air flow resistivity is changing in the range 2000< σ <10000 and the results are illustrated in Fig. 5. Also for group III, the values are c_{avg}=1.131, c'_{avg}=0.672 and 1000< σ <1800 , then Fig. 6 shows the result.

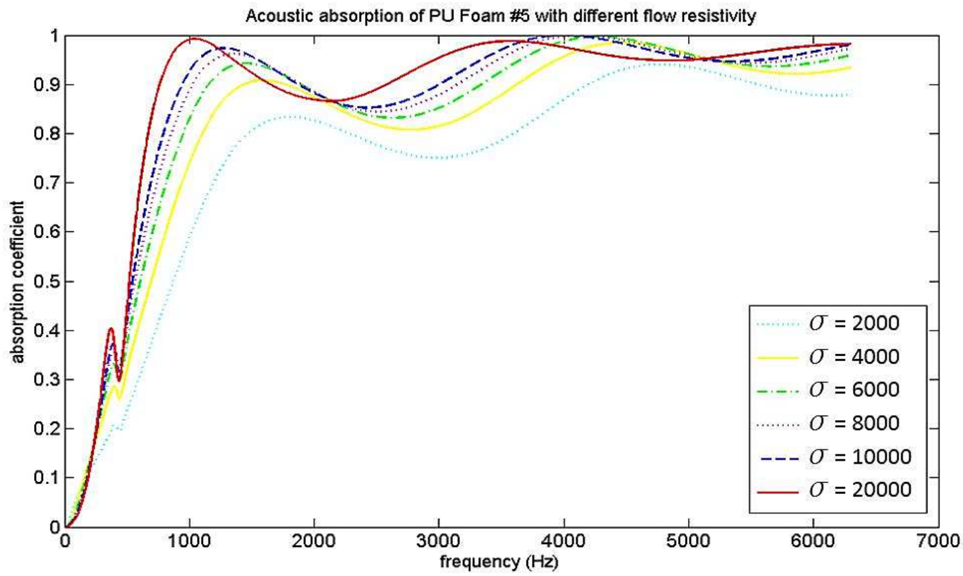

Fig. 5. Sound absorption coefficient of PU foam group II for different values of $\boldsymbol{\sigma}$, $\boldsymbol{\Lambda}$ and $\boldsymbol{\Lambda'}$

As it is clear from Figs. 4-6, an increase in the air flow resistivity with corresponding reductions of Λ and Λ' (Eqs. (2) and (4)) leads to an enhancement of absorption coefficient in the whole frequency range. In the case of partially reticulated foam, Fig. 5, beside the mentioned outcome, improvement of sound absorption efficiency at lower frequencies is another result. As a microstructural point of view, based on some experimental researches in this field [8, 13], if we reduce cell sizes of foams, it results into the increase of airflow resistivity, decrease of characteristic lengths and consequently improvement in sound absorption coefficient. However, an optimum value will exist for air flow resistivity because further increase of this parameter prevents acoustic wave to penetrate into the foam.

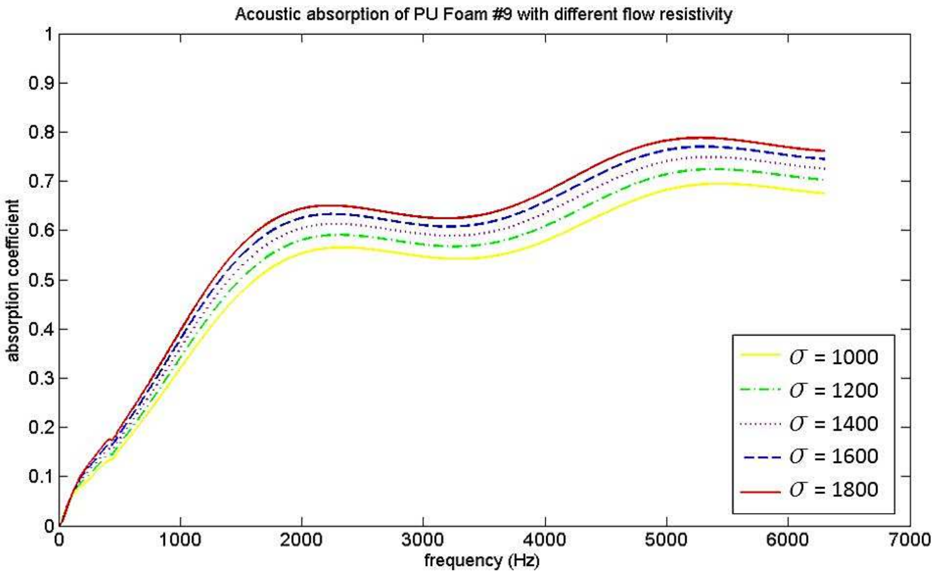

Fig. 6. Sound absorption coefficient of PU foam group III for different values of $\boldsymbol{\sigma}$, $\boldsymbol{\Lambda}$ and $\boldsymbol{\Lambda'}$

5.4. Effect of tortuosity on the sound absorption coefficient

A point was stated in Section 5.1 that the tortuosity of fully reticulated foam is independent of cell size (groups I and III of Table 1) and is nearly constant. But for partially reticulated foam, tortuosity changes with air flow resistivity and characteristic lengths. Now, to understand the approximate effect of tortuosity, in the lack of any proper mathematical relation, sample 6 of Table 1 is selected and two values are used for its tortuosity for evaluation of sound absorption coefficient. The obtained result is illustrated in Fig. 7.

According to Fig. 7, with the increase of tortuosity, sound absorption performance at lower frequencies is improved and its fluctuations are increased for frequencies more than 1000 *Hz*. Moreover, reduction of sound absorption is observed at high frequencies. The main structural factor which governs the value of tortuosity is the reticulation rate [8]. These two parameters are related to each other inversely. In fact, by the increase of closed cells in the structure, i.e. reduction of reticulation rate, foam sample would be more tortuous and vice versa. Accordingly, to improve sound absorption performance at lower frequencies, increasing the content of closed pore cells is advisable.

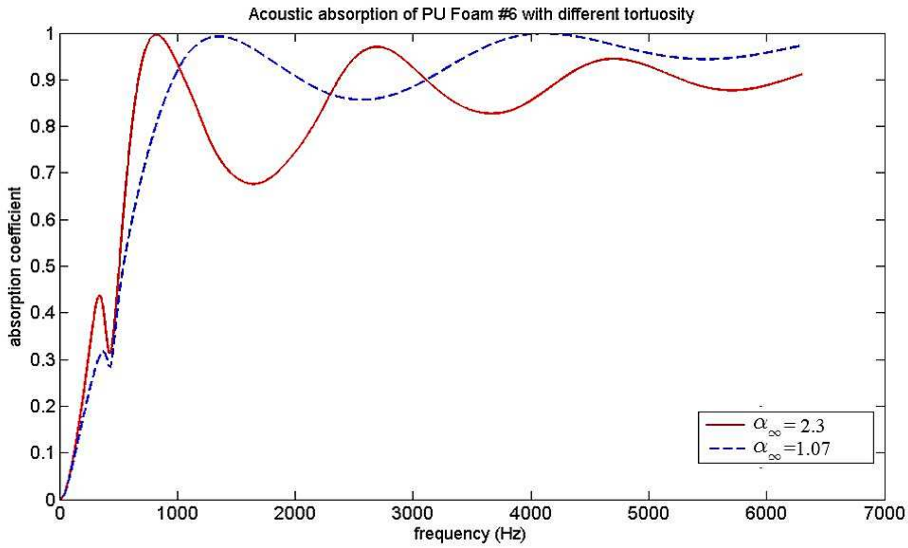

Fig. 7. Sound absorption coefficient of PU Foam #6 for two different values of tortuosity

6. Conclusion

In this paper, the issue of non-acoustic parameters' effect on the sound absorption coefficient of polyurethane foams has been scrutinized. Indeed, each of these parameters is sensitive to any change in others, therefore, some basic facts have been stated which make it possible to examine their effects individually. The results show that increasing porosity does not have great influence on the absorption behaviour of polyurethane foams. Except after a special value of porosity, an irregular decrease of sound absorption is observed. Increase of air flow resistivity and corresponding reduction of characteristic lengths enhance the sound absorption to higher values. Besides, increase of tortuosity decreases the frequency of maximum sound absorption coefficient. As non-acoustic properties are dependent to cellular structure of foams, the results of this study can be used in order to make a foam with a desirable high sound absorption performance.

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