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Delany-Bazley Model - A Powerful Tool in Optimizing the Acoustic Characteristics of Passive Fibrous Sound Absorbers for Noise Reduction Applications

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Abstract

Delaney Bazley model is the widely used empirical model for extracting the acoustic characteristics of passive acoustic absorbers made of porous layers of fibrous materials. This model provides the characteristic impedance and wave propagation number of the fibrous absorbers in terms of their microstructural intrinsic properties and the extrinsic properties of the specimen. The frequency dependent characteristic impedance and propagation constant of two different material based porous fibrous layers of different fiber diameters are investigated for the purpose of extracting the frequency dependent characteristic impedance and propagation constant. The frequency dependence of the characteristic impedance and wave propagation number is analyzed for these two samples. These parameters itself are utilized for extracting and analyzing the dependence of the acoustic reflection coefficient and absorption coefficient on the acoustic field frequency. The influence of the extrinsic property such as thickness of the material on the same is analyzed. The fiber diameter plays a crucial role in determining the acoustic performance. The samples of different fiber diameters are investigated for their frequency dependent acoustic absorption in order to understand the relevance of fiber diameter in determining the frequency response of the acoustic absorption coefficient.

Keywords: Passive Sound Absorber, Acoustic Absorption Coefficient, characteristic impedance, porous layer

1. INTRODUCTION

Passive and active acoustic absorbers are widely used in order to control noise. Noise controlling is essential in this modern world of fast industrialization and technological development. The adverse impacts of noise pollution on human health, environment, wildlife, aquatic life and our ecosystem are at its zenith concern during this period. Even the technological world itself is under the threat of noise pollution. Noise and vibration above a particular level induces wear and tear in the sensitive parts of certain sophisticated modern instruments which in turn reduces their efficiency, lifetime and performance [1]. At this juncture it is essential to develop, fabricate and optimize the acoustic characteristics of the passive acoustic absorbing materials for noise reduction applications according to the requirement. Active noise controllers are less energy efficient compared to the passive ones as they require external energy resources for their performance even though they are more efficient in the low frequency noise reduction applications compared to the passive ones[2]. So it is essential to develop passive acoustic absorbers with high performing capacity in the low frequency acoustic region.

2. ACOUSTIC ABSORBERS

Natural as well as synthetic materials can be used for passive noise controlling. The microscopic structure and surface morphology of these passive absorbers are preferable for enhancing the noise reduction mechanisms happening within them. The tubular, granular and the fibrous nature of these materials are favorable for sound absorption [3]. Natural ecofriendly fibrous materials are getting more demand currently for this purpose because of the increased concern about the preservation of the environment and their prominent role as reinforcement element in the composites. Natural and synthetic fiber reinforced composites find application in different industrial, domestic and medical fields as the inherent fiber properties enhance their efficiency in the particular application of interest. The fiber diameter, fiber length, and the orientation of the fibers can be properly selected so as to modify the physical and mechanical properties of the composites. The recent development in the composite making technology, the advancement in nanotechnology and the technological revolution help in developing the composites with required physical, chemical, optical, acoustical and electrical properties. The commonly used natural fibers include coir, hemp, kenaf, jute, date palm fiber etc.[3].

Natural fibers are preferred as the designing materials in this study for developing passive acoustic absorbers based on Delaney Bazley modeling because of their biodegradable cum ecofriendly nature. The variability in the fiber diameter and the desirable physical cum mechanical properties of these natural lignocellulosic fibers make them an attractive candidate in this concern. The natural fibers available in a wide range of fiber diameters varying from 1-100 µm are helpful in this particular designing. The porous structure of these fibrous samples is favorable for sound absorption. When porosity is increased the viscous loss of sound energy is increased and hence the acoustic absorption is increased. Hence it is important to analyze the crucial role of the variability in fiber diameter, airflow resistivity, thickness and porosity of the sample in controlling the acoustic properties so as to optimize these parameters to obtain a sample with maximum acoustic absorption in the required frequency range of interest. In order to achieve this aim acoustic characterization and their optimization is done with the help of Delaney Bazley modeling [4]. Delaney Bazley model is used for visualizing the frequency response of the characteristic impedance ,wave propagation number, reflection coefficient, absorption coefficient of the acoustic filed inside the porous media. The model is used to investigate the influence of airflow resistivity ,fiber diameter and thickness of the sample on the acoustic characteristics for selected porous layered samples of different fiber diameter and absorber thickness.

3. CHARACTERISTIC ACOUSTIC PARAMETERS WHICH DETERMINE THE PERFORMANCE OF FIBROUS PASSIVE ABSORBERS ACCORDING TO DELANY-BAZLEY MODEL

The acoustic absorption coefficient α, the reflection coefficient R, the characteristic impedance Z_c and the propagation constant K_c are some of the important characteristic acoustic properties whose values determines the performance of a passive acoustic absorber [4]. In this context we have to analyze and determine these constants and their explicit and implicit dependence on the microscopic and macroscopic structural parameters of the absorber. The absorption coefficient is given by the relation

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

The acoustic absorption coefficient can be determined if the coefficient of reflection is known .The reflection coefficient can be determined from the relation give below

$$R=\frac{Zs-\rho_0 oc}{Zs+\rho_0 c} \tag{2}$$

In the above equation Z_s is known as the surface acoustic impedance and $\rho_o c$ is the characteristic impedance of the medium through which sound is propagated. Where ρ_o is the density of the medium and c is the velocity of sound in the medium.

In the case of a rigid passive absorber the surface impedance Zs is given by the formula

$$Zs=-jZ_c\cot(K_c\mathrm{d}) \tag{3}$$

Where Z_c is the characteristic impedance of the sample and K_c is the propagation constant and d is the thickness of the sample.

In the present investigation the acoustic characteristics of the fibrous material under investigation is modeled for developing the passive absorber with optimum acoustic properties. The Delaney Bazeley modeling is used for this particular purpose and the equations for predicting the acoustic characteristics are given by the relation given below[4-6].

$$Z_c=\left\{p_0\,c(1+0.0571\left(\frac{p_0 f}{\sigma}\right)^{-0.754}-j0.087\left(\frac{p_0 f}{\sigma}\right)^{-0.732}\right\} \tag{4}$$

$$K_c=\frac{\omega}{c}\left\{1+0.0978\left(\frac{p_0 f}{\sigma}\right)^{-0.7}-j0.189\left(\frac{p_0 f}{\sigma}\right)^{-0.595}\right\} \tag{5}$$

Where σ is the flow resistivity of the medium and f is the frequency of the propagating sound wave. ρ_o is the density of the ambient fluid medium of propagation of sound. The angular frequency ω is given in terms of the acoustic frequency f by the expression ω=2πf.

For normal incidence the airflow resistivity [7-8] is given by the formula

$$\sigma=\frac{10.56\eta(1-\varepsilon)^{1.531}}{a^2\ \varepsilon^3} \tag{6}$$

Where σ is the airflow resistivity, ε is the porosity of the sample and η is the viscosity of the ambient fluid medium. The fiber diameter is given by the parameter a. The parameter ε depends on the density of the bulk material and the density of the fiber [8-9]. The porosity is given by the formula

$$\varepsilon=1-\frac{\rho_m}{\rho_f} \tag{7}$$

Where ρ_m is the density of the bulk material and ρ_f is the density of the fiber material.

Using the above model the model the surface impedance, Propagation constant ,air flow resistivity and the porosity of the medium can be determined which in turn helps to determine the Reflection coefficient and the absorption coefficient.

4. ACOUSTIC CHARACTERIZATION OF THE FIBROUS MATERIAL USING THE DELANY-BAZLEY MODEL

The acoustic characterization of the porous layers of the selected fibrous materials is done using the empirical model proposed by Delany-Bazley Model. The acoustic characteristics are analyzed in the frequency region from 0-6000Hz. The natural fiber based porous layer structures are used for this particular purpose. Cotton and jute fibers are selected as the representatives in this particular modeling in order to calculate the propagation constant and characteristic impedance during the sound propagation in the frequency range of 0-6000Hz. The variation of the above parameters with respect to frequency is calculated using the formula proposed by this model. In this particular study it is tried to optimize the fiber diameter and thickness of these fiber based porous acoustic layers for acoustic absorption in the desired frequency region of interest using this Delaney Bazeley model. The cotton and jute fiber based porous acoustic layers consisting of fibers of fiber diameter 6µm (Sample A) and 31µm (sample B) are used in this particular context for modeling. The porosity and airflow resistivity of the samples are determined using equations (6) and (7) using the values of fiber a, ε, η, ρ and ρ_m. The values for σ, f, ω, c, ρ_0 helps in determining the frequency dependent characteristic impedance and propagation constant of the acoustic field propagating through the porous layer of the passive acoustic absorber [8-9]. The values of these characteristic impedance and propagation constant help to determine the frequency dependent surface acoustic impedance and reflection coefficient of the material. The absolute value of the reflection coefficient helps to determine the frequency dependent sound absorption coefficient.

5. RESULT AND DISCUSSION

The frequency response of the acoustic absorption coefficient in the frequency range 0-6000Hz for the porous layered sample A of thickness 20mm is shown in figure.1. From the figure it is clear that the maximum acoustic absorption is obtained in the frequency region 4000-6000Hz. The frequency response of the propagation constant kc and that of the characteristic impedance zc for the sample A is shown in figure.2 and figure.3 respectively. The variation of the real and imaginary parts of the kc and zc with frequency is separately included in the figure.2 and figure.3. The frequency response of the acoustic absorption coefficient of sample B is shown in figure.4. It is clear that this particular sample B behaves as poor passive absorber compared to the sample A which performs as a good acoustic absorber in the frequency range of 4000-6000Hz. The frequency response of the propagation constant kc and characteristic impedance zc of the sample B is shown in figure.5 and figure.6 respectively. The variation of the real and imaginary part of kc and zc with frequency are separately shown in the figure.5 and figure.6 respectively for sample B.

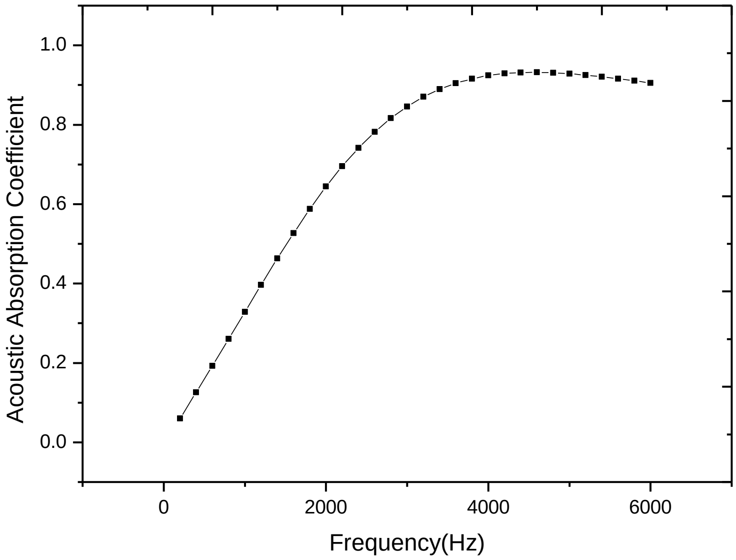

Figure.1 Frequency response of the acoustic absorption coefficient for Sample A

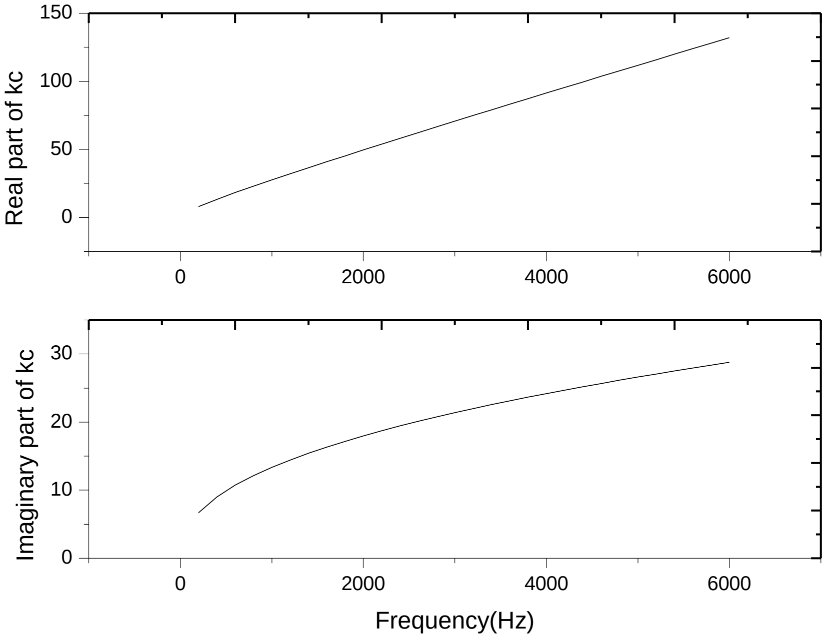

Figure.2. Frequency response of the real and imaginary parts of the propagation constant for sample A

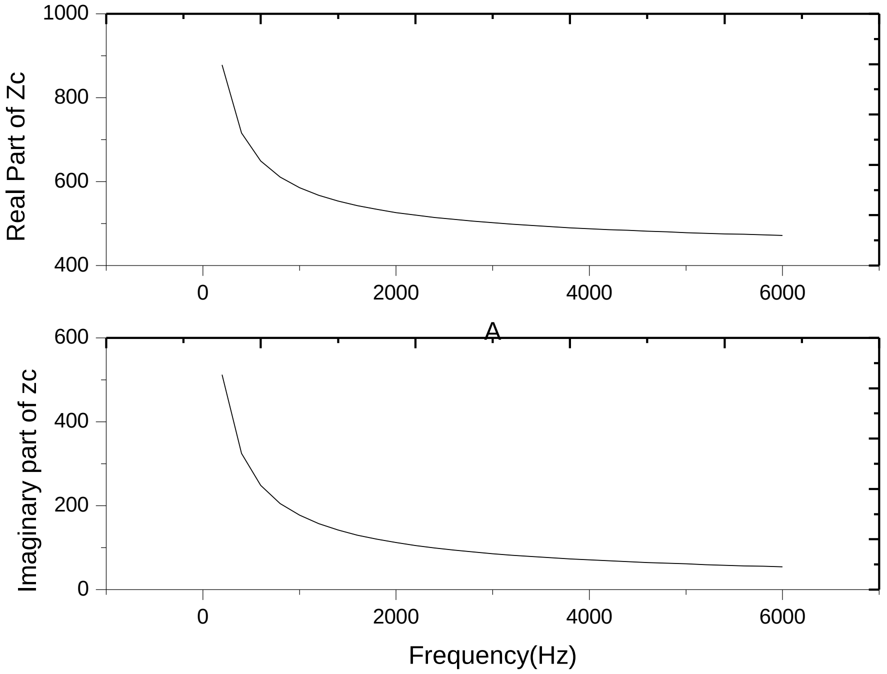

Figure.3. Frequency response of the real and imaginary parts of the characteristic impedance for sample A

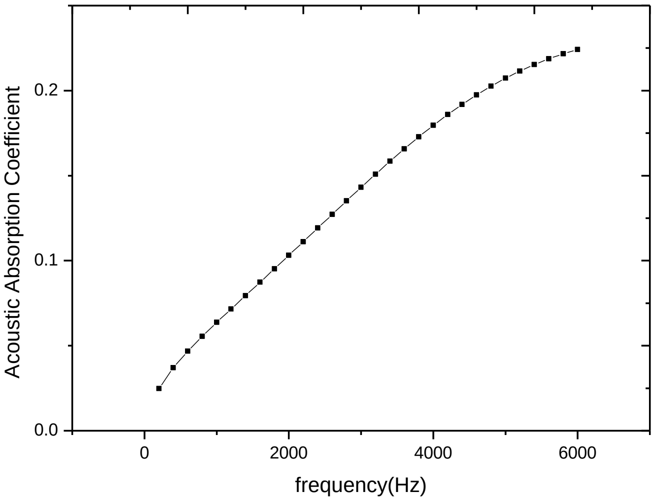

Figure.4. Frequency response of the acoustic absorption coefficient for sample B

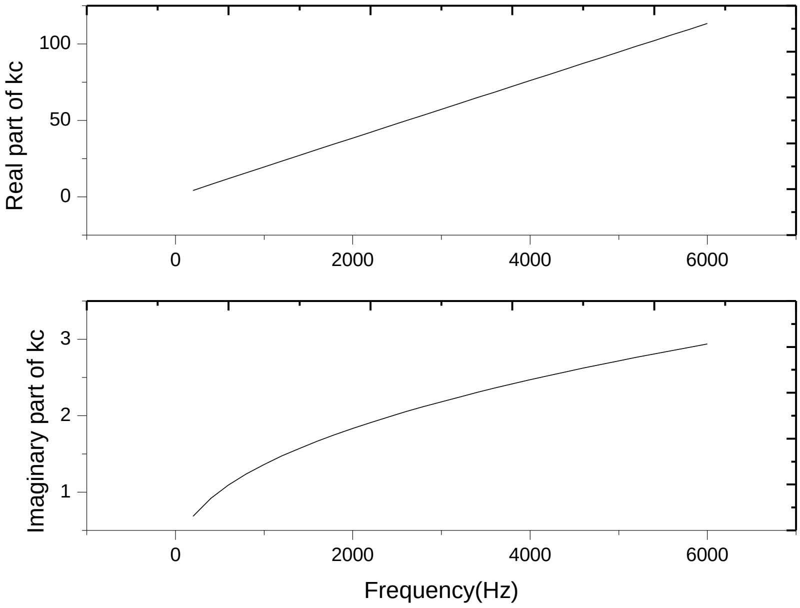

Figure.5 Frequency response of the real and imaginary parts of the propagation constant for sample B

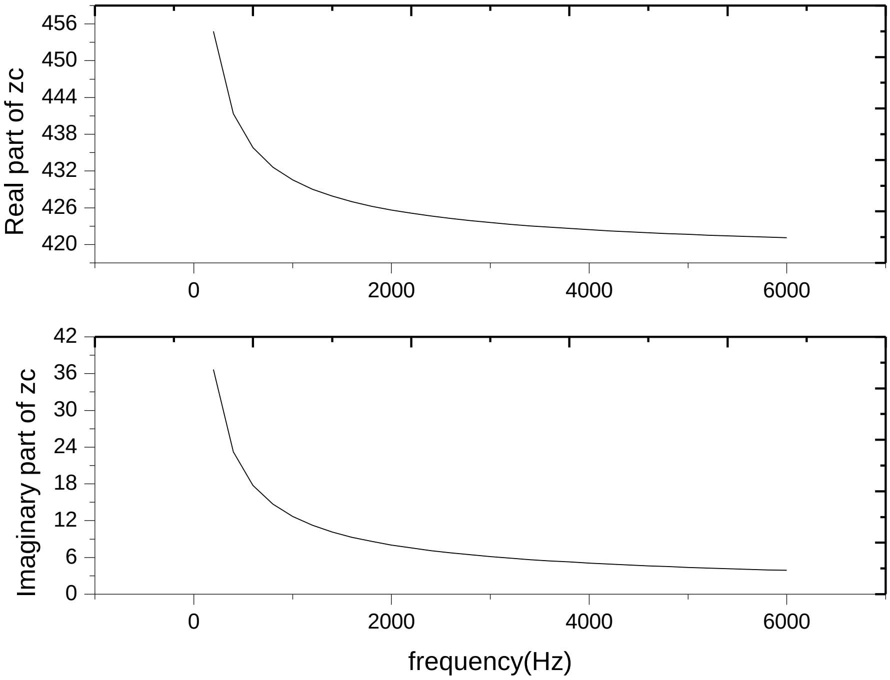

Figure.6. Frequency response of the real and imaginary parts of the characteristic impedance for sample B

This particular model is utilized in order to understand the effect of variation of the extrinsic parameters of the sample on the frequency response of the acoustic absorption coefficient. For this purpose the thickness of the porous layer of the material A is varied for seven different values of thickness d of the sample. Frequency response of the acoustic absorption coefficient of the sample A corresponding to seven different thickness (10mm, 12mm, 15mm, 18mm, 20mm, 50mm and 100mm) is shown in figure.7. It is clear from these curves that the acoustic absorption increases with thickness. When the thickness has reached an optimum value the material behaves like a perfect absorber with maximum absorption close to unity almost in the full frequency range under consideration between 0-6000Hz. It is clear that after reaching this optimum value of thickness of the material, further increase in thickness has no effect on the frequency response of the absorption coefficient. The frequency response of the acoustic absorption coefficient of the sample B of varying thickness (10mm, 12mm, 20mm, 100mm and 200mm) is shown in figure.9. In the case of the sample B the performance of the sample is not that much enhanced even though the thickness is increased to a considerable extend of 200mm. In the case of the sample A of low fiber diameter the performance was good and when the thickness of the specimen is increased to 50 mm the sample behaved as a perfect acoustic absorber. In the case of the sample B of high fiber diameter the performance is so poor even in the thickness range of 100mm-200mm. Thus the model is helpful in analyzing the effect of the variation of one of the extrinsic parameter –the thickness of the sample -on the frequency response of the acoustic absorption coefficient.

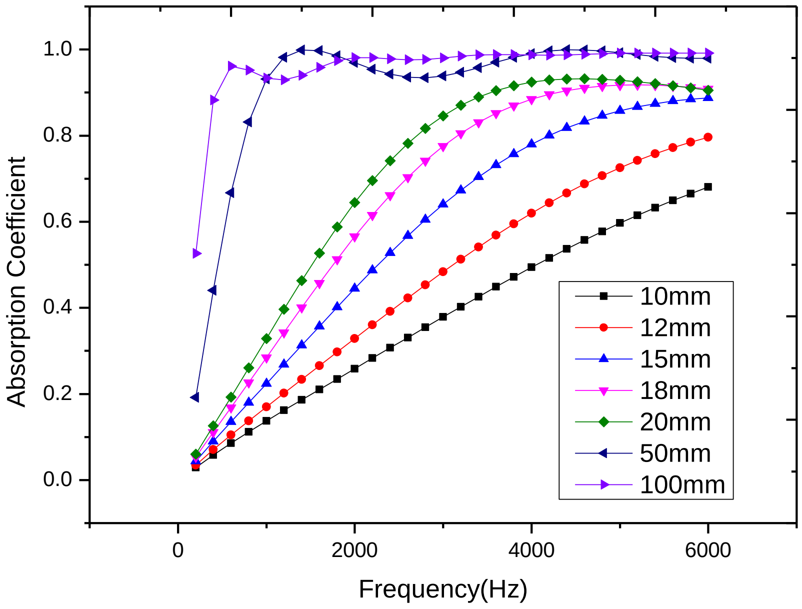

Figure.7. Variation of the frequency response of the acoustic absorption coefficient with thickness - sample A.

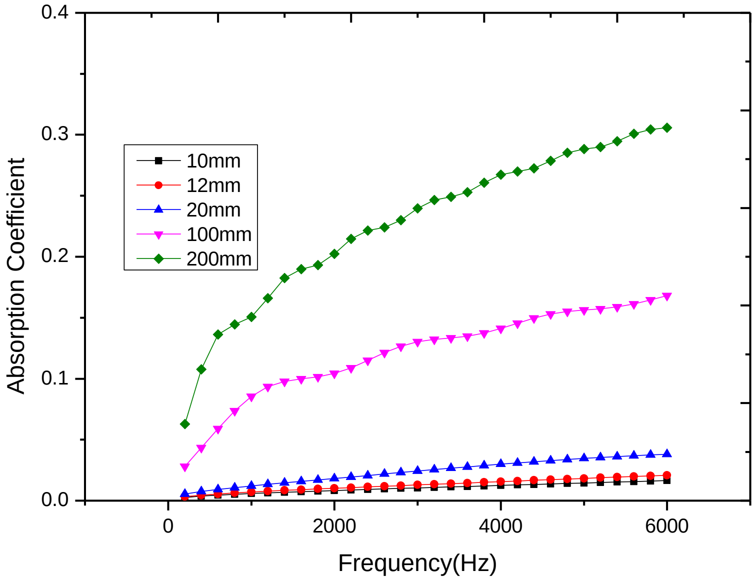

Figure.8. Variation of the frequency response of the acoustic absorption coefficient with thickness-sample B

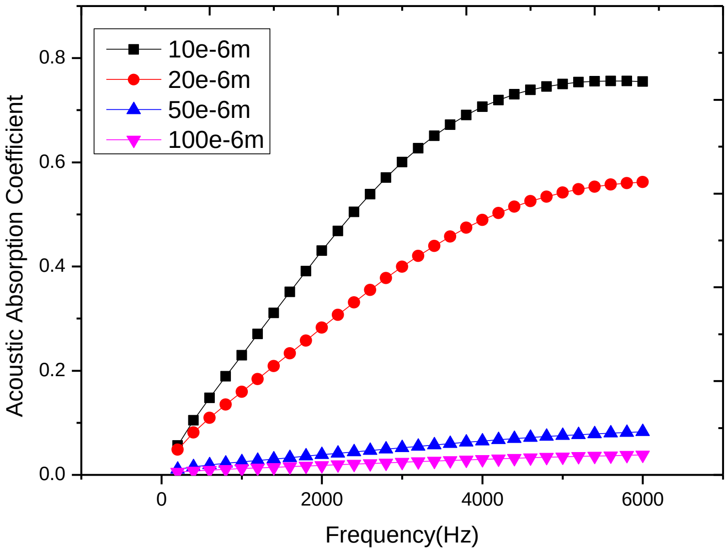

Figure 9. Variation of the frequency response of the acoustic absorption coefficient with fiber diameter- sample A.

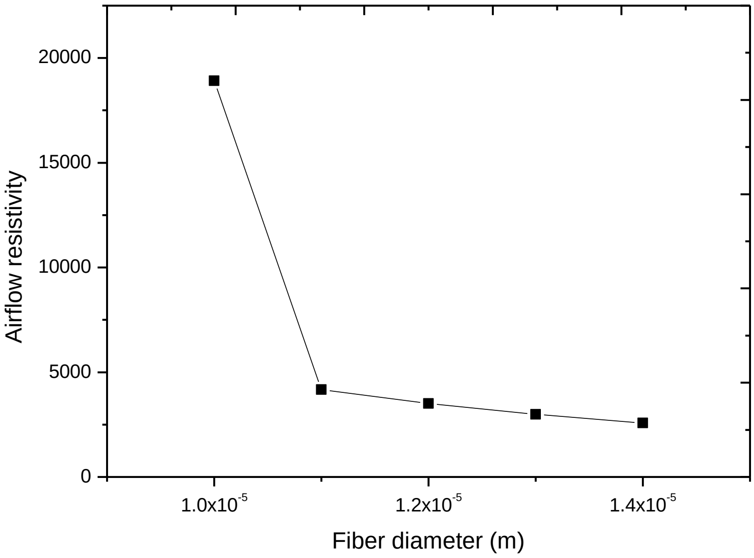

Figure.10. Variation of the airflow resistivity with fiber diameter.

The comparison of the frequency response of acoustic absorption coefficient and the effect of thickness variation on the frequency response of the acoustic absorption coefficient in the case of sample A and sample B it is clear that the fiber diameter is a crucial parameter in deciding whether it is a good acoustic absorber or not. In order to understand the effect of fiber diameter in determining the acoustic performance of the sample the fiber radius of the sample A is varied from 10µm to 100 µm. The frequency response of the acoustic absorption coefficient based on this particular model for variable fiber radius (10 µm, 20 µm, 50 µm and 100 µm) is shown in the figure.10. It is clear from this figure that the fiber diameter is crucial in determining the frequency response of the acoustic absorption coefficient. It is evident from the graph (figue.10) that the absorption performance is better when the fiber diameter is minimum and when the fiber diameter is increased the acoustic absorption decreases. The decrease in acoustic absorption as result of the increase in fiber diameter is attributed to the decrease in the flow resistivity. The air flow resistivity is decreased when the fiber diameter is increased. The variation of air flow resistivity inside the sample as a result of the increase in fiber diameter is shown in figure.11. The graph clearly indicates that when the fiber diameter is increased the airflow resistivity of the sample decreases. As a result of the decrease in this parameter the acoustic absorption decreases. Thus the sample with high fiber diameter performs as a poor acoustic absorber compared to the one with low fiber diameter. It is clear from the graph that the airflow resistivity is very high when the fiber diameter is the minimum. This very high value of air flow resistivity corresponding to low value of fiber diameter causes high acoustic absorption.

6. CONCLUSION

The Delaney Bazley model is a powerful tool in extracting the acoustic parameters of the fibrous samples. The model reveals how fibrous materials can be properly designed for better acoustic performance in the desired frequency range of interest. The fibrous samples of desired fiber diameter with desired porous layer thickness can be optimized based on this empirical model. The significance of extrinsic parameters like thickness of the sample in determining the acoustic performance of the passive absorbers being explored using this model. The role of the intrinsic parameters such as diameter of the fiber in controlling the acoustic properties by influencing the airflow resistivity of the sample is revealed through this particular modeling as a tool. The relevance of the microstructural properties such as air flow resistivity and porosity of the sample in the context of noise controlling can thus be explored. The modeling study reveals that fibrous absorbers of low fiber diameter are good acoustic absorbers. In the case of samples of low fiber diameter the thin sample itself is enough for the noise reduction purpose. It also reveals that the fiber diameter controls the airflow resistivity of the sample. It is clear form this analysis that the airflow resistivity is very high in the case of samples of very low fiber diameter and so they performs as better acoustic absorbers compared to the ones having higher fiber diameter as seen in this analysis. Thus this model plays a significant role in optimizing the fibrous passive acoustic absorbers for various noise reduction applications.

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