Composites Communications 10 (2018) 25–35

Contents lists available at ScienceDirect

Composites Communications

journal homepage: www.elsevier.com/locate/coco

Porous materials for sound absorption

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ARTICLE INFO

Keywords:
Sound absorption
Foam
Fibers

ABSTRACT

With the rapid urbanization and fast growth of transportation, noise pollution has become one of the most serious environmental problems in front of the people worldwide, it usually causes various disorders and greatly affects the work efficiency and living standards of human beings. Reducing noise by using sound absorption materials is an important approach to lessen the harm of noise pollution. As the most abundantly used materials, porous materials combine the properties of lightweight, wide absorption frequency range and highly sound absorption ability, and they hold great potential in the field of sound absorption. In this review, the recent progress in the design and fabrication of porous sound absorption materials is summarized and highlighted. This review covers the introduction of the sound absorption mechanism and evolution of prediction models for porous sound absorption materials, and the research and development of the design concepts and fabrication of sound absorption foams and fibrous sound absorption materials. The review concludes with some perspectives and outlook for the porous sound absorption materials.

1. Introduction

Nowadays, with the fast urbanization and transport development, human beings worldwide usually face the serious problems induced by noise pollution, which has caused severe health risks such as annoyance, tinnitus, sleep disturbance, or even ischemic heart disease. Thereby controlling noise from the living environment is of great importance [1]. Release the damage by using sound absorption materials is an effectively method to solve these problems. Available commercial sound absorption materials could be generally divided into two categories: resonant sound absorption materials and porous sound absorption materials [2,3]. Resonant absorption materials mainly involved single Helmholtz resonator [4], perforated panels [5], and membrane absorbers [6]. These sound absorbers are based on the principle of internal resonance effect [7], which endowing these materials with good absorption properties in low frequency, whereas they often suffer from the disadvantage of narrow frequency band of sound absorption [8,9].

Porous sound absorption materials are composed of channels, cracks or cavities which allow the sound waves entering the materials. Sound energy is dissipated by thermal loss caused by the friction of air molecules with the pore walls, and viscous loss bring by the viscously of airflow within the materials. These energy consumption principles endow porous materials with broad frequency band for sound absorption [10,11]. Furthermore, Porous sound absorption materials, with the extraordinary properties such as low cost, easy molding, and reduction in weight, are acting as ideal materials for the controlling of noise in fields such as building and transportation [12–14]. Generally, the commonly used porous sound absorption materials can be classified as sound absorption foam and fibrous sound absorption materials. Sound absorbing foams are made up of cellular structures that connected with each other, while fibrous sound absorption materials contain lots of channels between the constructed fibers, and these fibers may be continuous filaments or staple fibers [15].

In this review, recent work on the design, fabrication and developments of porous sound absorption materials is summarized. This review is arranged into three parts: the mechanism of sound absorption, sound absorption foams, and fibrous sound absorption materials. Firstly, the mechanism and prediction models for porous sound absorption materials are introduced. Secondly, recent progress in the research of porous sound absorption materials is summarized, which are discussed by the classification of material category and construction form (Fig. 1). Finally, the perspective and outlook on the future development of porous sound absorption materials are concluded in this paper.

2. Mechanism of sound absorption

2.1. Principles of sound absorption

Despite of the differential in appearance, the mainly sound

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https://doi.org/10.1016/j.coco.2018.05.001
Received 12 April 2018; Received in revised form 6 May 2018; Accepted 8 May 2018
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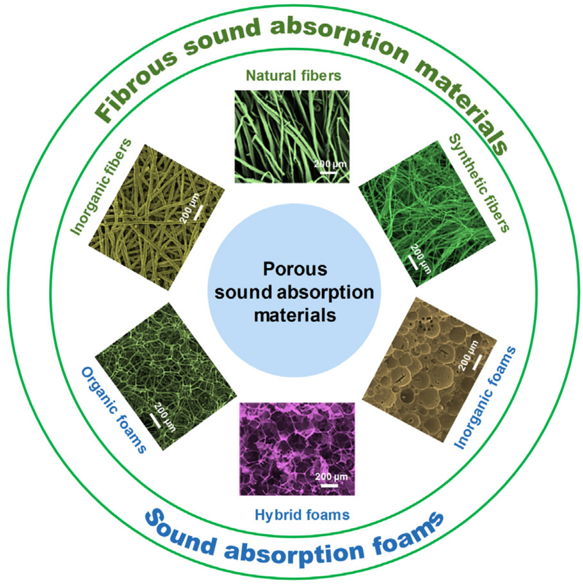

Fig. 1. Porous materials for sound absorption.

absorption mechanism of those porous sound absorption materials is similar with each other. When sound waves strike on the porous materials, three kinds of transformations are happened for the sound energy: reflection, absorption and transmission (Fig. 2a). The totally sound energy can be regarded as the sum of the energy been reflected, absorbed and transmitted [16]:

$$E_i = E_r + E_a + E_t \quad (1)$$

where E_i is the total incident sound energy, E_r is the sound energy of reflection, E_a is the sound energy of absorption, E_t is the sound energy of transmission.

Sound absorption coefficient α is used to quantify the dissipation abilities of porous sound absorption materials, which can be tested by impedance tube or reverberation chamber. α is described as the ratio of absorbed sound energy to the total incident sound energy:

$$\alpha = 1 - \frac{E_r + E_t}{E_i} = \frac{E_a}{E_i} \quad (2)$$

The consumption of sound energy in porous materials mainly follow the three principles: (1) Air molecules in the porous sound absorption materials would vibrate and rub with the pore walls, leading to the conversion of sound energy to heat and then dissipated; (2) when the longitudinal sound waves penetrate into the porous materials, the air in the pores are periodically compressed and released, resulting in the energy consumption during the process of energy transformation; (3) the sound energy would be converted into mechanical and heat energy through the resonance of pore walls (Fig. 2b) [17,18]. Correspondingly, there are three criteria to design porous sound absorbers: (1) the materials should consist of a considerable number of pores (such as cavities, channels or interstices); (2) the pores should in the proper size and interconnected with each other for the propagation of sound waves; (3) there should have continuous channels between the inner pores and the external surface of the materials [19].

2.2. Prediction models

The prediction models are usually used to theoretically calculate the energy consumption efficiency of the porous sound absorption materials, which could provide guidance for the structure design of porous sound absorption materials. Sound absorption coefficient can be predicted when surface acoustic impedance of the material is known. It can be calculated by:

$$\alpha = 1 - \left| \frac{Z_s - \rho_0 c_0}{Z_s + \rho_0 c_0} \right|^2 \quad (3)$$

Z_s is the surface impedance, $\rho_0 c_0$ represents the impedance of the air.

Up to now, several impedance prediction methods for porous sound absorption materials have been published [20]. Among which two approaches are commonly used to predict the sound absorption properties of porous sound absorption materials. The first one is a completely empirical approach exemplified by Delany and Bazley, which is obtained by fitting copious experimental data. Only one parameter (flow resistivity) is demanded for this model. Expressions of Delany-Bazley models are as follows [21]:

$$Z_c = \rho_0 c_0 \left[1 + 0.0571 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.754} - j0.087 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.732} \right] \quad (4)$$

$$k_c = \frac{\omega}{c_0} \left[1 + 0.0978 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.7} - j0.189 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.595} \right] \quad (5)$$

$$z_s = z_c \coth(-ik_c l_s) \quad (6)$$

where Z_s is the normalized acoustic surface impedance , σ is flow resistivity, ρ_0 is the air density, l_s is the thickness of porous materials, ω is the angular frequency that calculated by $\omega = 2\pi f$.

Although the theoretical and practical results matched well, the validity of the Delany-Bazely model is generally considered to be restricted to the range $0.01 < \rho_0 f/\sigma < 1$. In the following work, some amendments were subsequently made by Miki, Komatsu and other researchers, these models were established to make more accurate prediction, while the calculations become complex since more parameters were considered [22–24]. However, thermal conductive effect is not considered in the Delany-Bazley model, which limited the prediction accuracy. To solve this problem, phenomenological models are established by taking viscous effect and thermal conductive into consideration. Which regard the rigid pore frame as solid and the air in the pores as fluid [25].

The most commonly used semi-phenomenological model is the Johnson-Champoux-Allard (JCA) model [26]. Five physical parameters are involved: flow resistivity σ, open porosity ϕ, tortuosity α_∞, the viscous characteristic length Λ and the thermal characteristic length Λ'. The effective density ρ_e and the effective bulk modulus K_e are adopted to describe the viscous effects and thermal effects respectively, which

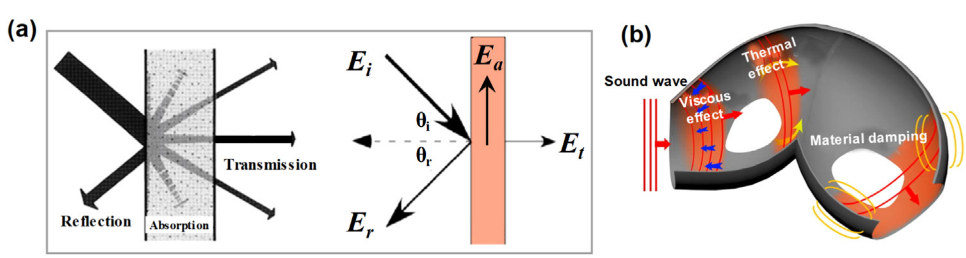

Fig. 2. (a) Schematic of the sound absorption process for porous materials [16]. © 2016, Elsevier B.V. (b) Schematic diagram showing the energy consumption mechanisms of porous sound absorption materials [17]. © 2017, American Institute of Physics.