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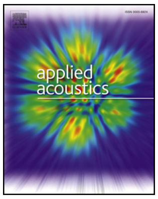

A study of some airflow resistivity models for multi-component polyester fiber assembly

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ABSTRACT

The airflow resistivity is a key parameter to predict accurately the acoustical properties of fibrous media. There is a large number of theoretical and empirical models which can be used to predict the airflow resistivity of this type of porous media. However, there is a lack of experimental data on the accuracy of these models in the case of multi-component fibrous media. This paper presents a detailed analysis of the accuracy of several existing models to predict airflow resistivity which make use of the porosity, bulk density and mean fibre diameter information. Three types of polyester (PET) materials made using regular PET, hollow PET and bi-component PET with a range of densities are chosen for this study. It is shown that some existing models largely under- or overestimate the airflow resistivity when compared with the measured values. A novel feature of this work is that it studies the relative performance of airflow resistivity prediction models that are based on the capillary channel theory and drag force theory. These two groups of models are then compared to some purely empirical models. It is found that the prediction error by some models is unacceptably high (e.g. > 20–30%). The results suggest that there are existing models which can predict the airflow resistivity of multi-component fibrous media with 8–10% accuracy.

1. Introduction

The airflow resistivity is one of the most critical parameters determining the sound absorption properties of a porous absorber. It is a measure of how easily air can enter a porous absorber and the resistance that airflow meets within a structure. Once the airflow resistivity is known, a series of theoretical or empirical models can be applied to predict the impedance and absorption coefficient of fibrous media [1]. The values of airflow resistivity vary largely between various type of common porous absorbent materials. It therefore gives some sense of how much sound energy may enter the material pores to be lost due to viscous and inertia effects. According to the direct airflow method detailed in the standard ISO 9053-1991 [2], the airflow resistivity is determined by an experiment where a sample of a porous material is placed in a tube, and a steady airflow is passed through the sample. The airflow velocity, u, the pressure drop between two sides of the sample, Δp, and the thickness of the sample, h, are measured [2]. The airflow resistivity, σ, of the material is then defined:

$$\sigma = \frac{\Delta p}{uh}, \tag{1}$$

Polyester fiber materials are innovative products which are becoming widespread sound absorbers. These recyclable and long lasting materials are replacing traditional glass wool and rock wool in many noise control applications. Traditionally, polyester fiber materials used in sound absorption applications were manufactured from mono-size fibers or single-component fibrous materials, i.e. materials composed of fibers with identical or similar diameter and shape. Recently, multi-component polyester materials have started to become more popular replacing single component polyester materials. However, there is limited amount of data on the acoustical and related non-acoustical properties of multi-component polyester materials [3]. Therefore, the major objective of this study is to measure the airflow resistivity for a representative range of fibrous media and use data to understand better the effect of fiber diameter distribution on the accuracy of model predictions.

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2. Review of previous works on airflow resistivity models

There are a large number of theoretical and empirical models to predict the airflow resistivity for fibrous and granular media. Good reviews of some of these models can be found in Refs. [4–6]. These models can be grouped into two main categories: theoretical models and empirical models. In this section, the previous works on airflow resistivity models will be introduced and we will review mathematical expressions from some existing models for the airflow resistivity for completeness. In Section 3 we will use these models to predict the airflow resistivity of multi-component polyester fiber.

2.1. Theoretical models

There are two main theories in airflow resistivity theoretical models: capillary channel theory and drag force theory. The airflow resistivity models established using capillary channel theory are based on the works of Hagen-Poiseuille, Kozeny and Carman, where the flow through the porous material is treated as a conduit flow between parallel cylindrical capillary tubes [7,8]. Davies presented a model to fit his own transverse permeability data for the flow through porous fibrous materials having a high fabric porosity (as high as 0.7) [9]. The airflow resistivity of fiber orientation along the flow direction was in the same form as the Kozeny-Carman equation, and the airflow resistivity of fiber orientation perpendicular to the flow direction was obtained using the lubrication approximation, assuming that the narrow gaps between adjacent cylinders dominate the flow resistance [10,11]. Pelegrinis et al. modified the Kozeny-Carmen model to obtain more accurate prediction for the airflow resistivity of uniform fiber diameter polyester material [12]. Lind-Nordgren and Göransson presented a scaling law applied to the airflow resistivity of porous materials having a porosity and tortuosity close to 1 [13]. However, it has been argued that those models based on capillary channel theory can be unsuitable for high porosity media in which the porosity is greater than 0.8 [8]. Airflow resistivity models based on capillary channel theory are summarized in Table 1.

There are also a number of airflow resistivity models which are based on drag force theory. In these models the fibers in the porous material that form the walls of the pores in the structure, are treated as obstacles to a straight flow of the fluid and it is assumed that the frame is rigid and that the fibers cannot be displaced [15]. The sum of all the ‘drags’ is assumed to be equal to the total resistance to flow in the porous material. Unlike capillary flow theory, drag force theory and unit cell models demonstrate the relationship between permeability and the internal structural architecture of the porous material. In drag force models, the fibers are assumed to be aligned unidirectionally in a periodic pattern such as a square, triangular or hexagonal array. The airflow resistivity of unidirectional fibrous materials can then be solved using the Navier-Stokes equation in the unit cell with appropriate boundary conditions [4]. One of the earliest equivalent dimensionless permeability for flow parallel to an array of fibers was developed by Langmuir [16]. Tarnow presented a new way to calculate the airflow resistivity of randomly placed parallel fibers based on Voronoi polygons [17]. In his study, Tarnow discussed a two-dimensional model consisting of parallel fibers randomly spaced for flow parallel and perpendicular to the fibers. A summary of these models is given in Table 2.

Table 1
Airflow resistivity models established using capillary channel theory.

Method	Airflow resistivity
Davies CN [9]	$\sigma = \frac{64\eta(1-\varepsilon)^{1.5}[1+56(1-\varepsilon)^3]}{d^2}$
Kozeny-Carman [8]	$\sigma = \frac{180\eta(1-\varepsilon)^2}{d^2\varepsilon^3}$
Lind-Nordgren [13]	$\sigma = \frac{128\eta(1-\varepsilon)^2}{d^2\varepsilon}$
Doutres et al. [14]	$\sigma = \frac{128\eta(1-\varepsilon)^2}{d^2}$
Pelegrinis et al. [12]	$\sigma = \frac{180\eta(1-\varepsilon)^2}{d^2}$

Note: η is the air dynamic viscosity, ε is the material porosity and d is the fiber diameter.

Table 2
Airflow resistivity models established using drag force theory.

Method	Airflow resistivity
Langmuir [16]	$\sigma = \frac{16\eta(1-\varepsilon)}{d^2\left[-\ln(1-\varepsilon)-1.5+2(1-\varepsilon)-\frac{(1-\varepsilon)^2}{2}\right]}$
Hasimoto [18]	$\sigma = \frac{32\eta(1-\varepsilon)}{d^2(-\ln(1-\varepsilon)-1.476)}$
Kuwabara [19]	$\sigma = \frac{32\eta(1-\varepsilon)}{d^2[-\ln(1-\varepsilon)-1.5+2(1-\varepsilon)-\frac{(1-\varepsilon)^2}{2}]}$
Happel [20]	A. Flow parallel to fibers $\sigma = \frac{72\eta(1-\varepsilon)}{d^2[-\ln(1-\varepsilon)-3+4(1-\varepsilon)-(1-\varepsilon)^2]}$ B. Flow perpendicular to fibers $\sigma = \frac{72\eta(1-\varepsilon)}{d^2\left[-\ln(1-\varepsilon)-\frac{1-(1-\varepsilon)^2}{1+(1-\varepsilon)^2}\right]}$
Tarnow [17]	Flow parallel to fibers A. Square lattice $\sigma = \frac{16\eta(1-\varepsilon)}{d^2[-\ln(1-\varepsilon)+0.5-2\varepsilon]}$ B. Random lattice $\sigma = \frac{16\eta(1-\varepsilon)}{d^2[-1.280\ln(1-\varepsilon)+0.526-2\varepsilon]}$ Flow perpendicular to fibers C. Square lattice $\sigma = \frac{16\eta(1-\varepsilon)}{d^2\{\ln[(1-\varepsilon)^{-1/2}]-0.5\varepsilon-0.25\varepsilon^2\}}$ D. Random lattice $\sigma = \frac{16\eta(1-\varepsilon)}{d^2[-0.640\ln(1-\varepsilon)+0.263-\varepsilon]}$

2.2. Empirical models

An empirical model of airflow resistivity was first introduced by Nichols, who suggested that the flow resistance, $\sigma h \sim (\rho h)^{1+x}/d^2$, where the adjustable parameter is $0.3 \leq x \leq 1$. This parameter value depends on the distribution of the fibers in material [21]. Based on the work by Nichols, Bies and Hansen presented a simple model which allows the calculation of the airflow resistivity of fibreglass starting from the values of its bulk density and fiber diameter [22]. Garai and Pompoli investigated the airflow resistivity of double fiber component polyester materials and extended the Bies and Hansen model to predict the flow resistivity of polyester fibers [23]. Manning and Panneton analyzed the acoustic behavior of shoddy fiber materials manufactured by three different methods: mechanical bonding, thermal bonding, and resin bonding. They established three simple airflow resistivity models based on weight-of-evidence approach [24]. A summary of the equations for these empirical models is given in Table 3.

3. Materials and methods

One polyester nonwoven material prepared by vibrating perpendicular technology [25] at the Technical University of Liberec, Czech Republic, as well as two types of commercially available polyester nonwoven materials which were separately made by vibrating perpendicular technology and rotating perpendicular technology were selected for this study. Sample WM was prepared by rotating perpendicular technology; samples ST T1 and ST T2 were produced by vibrating perpendicular technology [26]. Fig. 1(a) is photographs which illustrate the dominant angle of fiber orientation of samples WM, ST T1 and ST T2. In this study, the fiber orientation angle was defined as the angle