Advanced Fibrous Materials for Acoustic Performance

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SUMMARY OF THE THESIS

Komise pro obhajobu disertační práce

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Abstract

The objective of this study was to examine multi-functional properties of high-loft perpendicularly-laid nonwoven fabrics, which can be used to noise reduction application at building and automotive field. It presents an experimental and numerical investigation on acoustic properties of perpendicularly-laid nonwoven fabrics. Perpendicularly-laid nonwoven samples were made by two different manufacturing techniques: vibration and rotating perpendicular lapper. Normally incident sound absorption coefficient and surface impedance were measured by Brüel and Kjær type 4206 impedance tube. Several airflow resistivity models grouped in theoretical and empirical categories were used to study the suitable model for perpendicularly-laid nonwoven fabrics. The commonly used impedance models such as Delany-Bazley, Miki, Garai-Pompoli and Komatsu models were applied to predict the acoustic properties. The measured and predicted values were compared to figure out the accuracy of the existing models. The potential compression mechanism of the nonwoven fabric was identified with support of the compression stress-strain curve at different compression stages. Perpendicularly-laid nonwoven fabrics have special thermal and air permeability behavior compared with traditional cross-laid nonwovens due to their through-plane fiber orientation. Hence this research work also investigates the influence of different structural parameters of perpendicularly-laid nonwoven fabrics, such as areal density, porosity, thickness, on thermal properties and air permeability. The potential relationships between thermal resistivity, air permeability and acoustic properties were also investigated.

This work also investigated sound absorption performance of aerogel based nonwoven fabrics. Polyester/polyethylene nonwovens embedded with hydrophobic amorphous silica aerogel were chosen for sound absorption measurements.

Statistical analysis software, Originlab 8.5 and Matlab_R2017a were used to conduct all the statistical results in this study. The findings are significant and can be used for further study in the areas of sound absorption behavior of fibrous materials, the application of perpendicularly-laid nonwoven fabrics for the noise treatment application in building and automotive fields.

Keywords: perpendicularly-laid nonwoven; acoustic properties; thermal resistivity; airflow resistivity; compressibility; impedance models

Abstrakt

Cílem této práce bylo prozkoumat multifunkční vlastnosti vysoko-loftových kolmo kladených netkaných textilií, které mohou být aplikovány ke snížení hluku v oblasti stavebnictví a automobilového průmyslu. Představuje experimentální a numerické vyšetřování akustických vlastností kolmo kladených netkaných textilií. Kolmo kladené vzorky z netkané textilie byly vyrobeny dvěma různými výrobními postupy: vibracemi a rotujícími kolmými lamelami. Obvykle koeficient absorpce hluku a povrchová impedance byly měřeny impedanční trubkou typu Brüel a Kjær 4206. Několik modelů odporového proudu vzduchu seskupených v teoretických a empirických kategoriích bylo použito ke studiu vhodného modelu pro kolmo kladené netkané materiály. Pro předpovědi akustických vlastností byly použity běžně používané impedanční modely jako modely Delany-Bazley, Miki, Garai-Pompoli a Komatsu. Naměřené a předpovězené hodnoty byly porovnány s výpočtem přesnosti stávajících modelů. Potenciální kompresní mechanismus netkané textilie byl identifikován s podporou kompresní křivky napětí-deformace, práce a účinnosti v různých kompresních stupních. Kolmo kladené netkané textilie mají zvláštní tepelnou a vzduchovou propustnost ve srovnání s tradičními netkanámi vrstvami z důvodu jejich orientace přes uvnitř vlákenné vrstvy. Proto tato výzkumná práce také zkoumá vliv různých strukturálních parametrů kolmo kladených netkaných textilií, jako je plošná hustota, pórovitost, tloušťka, na tepelné vlastnosti a propustnost vzduchu. Rovněž byly zkoumány potenciální vztahy mezi tepelným odporem, propustností pro vzduch a akustickými vlastnostmi.

Tato práce také zkoumala výkon absorpce zvuku z netkaných textilií na bázi aerogelu. Pro měření zvukové pohltivosti byly vybrány polyesterové / polyethylenové netkané textilie opatřené hydrofobním amorfním oxidem křemičitým.

Statistický analytický software, Originlab 8.5 a Matlab_R2017a, byl použit k provádění všech statistických výsledků v této studii. Zjištění jsou významná a mohou být použity pro další studium v oblastech chování pohlcování zvuku vláknitých materiálů, aplikací kolmo kladených netkaných textilií pohlcování hluku v budovách a automobilech.

Klíčová slova: kolmo kladené netkané textilie; akustické vlastnosti; tepelný odpor; proudění vzduchu; stlačitelnost; impedanční modely

Summary

1 Introduction

Noise, produced by household gadgets, big trucks, vehicles and motorbikes on the road, jet planes and helicopters hovering over cities and loud speakers, is considered as environmental pollution and becoming an increasing public health concern because it could cause a lot of problems such as stress related illnesses, speech interference, hearing loss, sleep disruption and so on. Most importantly, the immediate and acute effect of noise pollution to a person will impair the hearing if it lasts for a period of time. Prolonged exposure to impulsive noise to a person will damage their eardrum, which may result in a permanent hearing impairment. Moreover, health effects of noise like anxiety and stress reaction may bring physiological manifestations, such as headaches, feeling of fatigue, irritability and nervousness.[1]

In order to minimize the adverse effect caused by noise pollution, a variety of ways are available to reduce noise. The most efficient and classical solution to the problem has been the elimination of noise at source, but this may not always be possible.[2] Therefore, the reduction of noise emission is usually accomplished by noise isolation and absorption methods. The most common one is to use porous sound absorber to disseminate energy and turn it into heat.[3] A porous sound-absorbing material is a solid that contains cavities, channels or interstices so that sound waves are able to enter through them. As porous material, fibrous textile is widely used in automotive and building industries for noise control. It has been considered to be ideal sound absorber material because of its high porosity, high specific surface area, low-cost, light-weight, no pollution and high-efficient absorbing ability.[2, 4] Nonwoven is one kind of the most common porous sound-absorbing material. Perpendicularly-laid nonwoven, a typical high-loft nonwoven structure, is widely used for thermal and acoustic comfort in automobile industry.[5-10] Due to the majority of fibers orientated in the vertical plane, perpendicularly-laid nonwovens exhibit high resistance to compression and excellent elastic recovery after repeated loading. Moreover, because of their thermal bonded structure and high initial thickness, perpendicularly-laid nonwovens with varying thicknesses can be obtained through thermal treatment. Based on these characteristics, perpendicularly-laid nonwovens can be used in many places of automotive for sound and thermal insulation, such as under bonnet, door panels, headliners, A-B-C pillars and luggage compartment.

Hence, the current study relies entirely on objective measures of perpendicularly-laid nonwoven fabrics for evaluating the acoustic and non-acoustic properties like sound absorption coefficient, characteristic impedance, airflow resistivity, compression, thermal resistivity and air permeability. This research aims to provide an advanced high-loft structure nonwoven material for noise reduction to replace the tradition sound-absorbing materials such as glass fiber and mineral wool mat. A thorough study of the properties of the processed materials was performed.

2 Purpose and the aim of the Thesis

In this work, two types of manufacturing technologies, STRUTO and WAVEMAKER, were used to prepare nonwoven samples. The purpose of this study is to understand the acoustic, compression and thermal performance of perpendicularly-laid nonwoven. The major objectives of this research are as follows:

2.1 Studies on acoustic performance of perpendicularly-laid nonwovens with respect to their structural parameters

The Brüel and Kjær impedance and Materiacustica tubes were employed for sound absorption and impedance measurements to study the acoustic properties of nonwoven fabrics. Nonwoven fabrics with varying thickness and density were prepared to investigate the effect of manufacturing technologies, fabric porosity, thickness and areal density on the sound absorption ability of nonwoven samples.

2.2 Investigation of compression and resiliency in 3D corrugated nonwovens

Researchers have studied the compression properties of perpendicularly-laid nonwovens, but there is no exiting paper focusing on the influence of fiber orientation on compression performance. In this research, nonwoven samples with different fiber orientation have been chosen to investigate the effect of fiber orientation on compression property of perpendicularly-laid nonwoven fabric. The perpendicularly-laid nonwoven samples were heat treated to change the fiber orientation angle. Besides, the effect of manufacturing technology and fabric density on compression property has been studied. The compression energy and compression load of perpendicularly-laid were measured by using TIRATEST 2300. It was found that the fiber orientation angle sharply decreases with the increase of load during heat treatment. Perpendicularly-laid nonwovens with higher fiber orientation angle exhibit higher compression resistance. Shearing deformation occurs during compression process of perpendicularly-laid nonwovens. Fiber orientation angle decreases with the increase of thickness reduction.

2.3 Study of sound absorption property in relation to thermal properties

Thermal and acoustic properties are very important for the materials applied in automotives and buildings for heat and sound insulation applications. The Alambeta device was used to measure the thermal properties of perpendicularly-laid nonwovens. Based on the results of acoustic and thermal properties, the relationship between these two properties has been studied. In this research, the main purpose is to explore their inter-relation and further understand both acoustic performance and thermal properties of nonwoven fabrics. Most importantly, the result may provide a new approach to evaluate acoustic performance by simple measurement of thermal properties.

2.4 Investigation of acoustic behavior and air permeability of perpendicularly-laid nonwovens

This work also deals with the study of acoustic performance of perpendicularly-laid nonwovens and their relation to fabric air permeability. Air permeability of perpendicularly-laid nonwovens was examined by using FX3300 Textech Air Permeability Tester. It was observed that the sound absorption capacity was inversely proportional to air permeability. It was concluded that air permeability can be used as a criterion of sound absorption behavior of perpendicularly-laid nonwovens, a lower air permeability suggested a better sound absorption performance for perpendicularly-laid nonwoven fabric.

2.5 Investigation on sound absorption properties of aerogel based nonwovens

This work presents an investigation on sound absorption performance of aerogel based nonwoven fabrics. Polyester/polyethylene nonwovens embedded with hydrophobic amorphous silica aerogel were chosen for sound absorption measurements. The sound absorption coefficient (SAC) of single and multilayered of aerogel based nonwovens blankets was tested by Brüel and Kjær impedance tube, the noise reduction coefficient (NRC) was used for numerical analysis.

2.6 Study on some theoretical models of airflow resistivity for multi-component polyester perpendicularly-laid nonwovens

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 study presents a detailed analysis of the accuracy of several existing models to predict airflow resistivity which make use of the bulk density and mean fiber diameter information. The results shown that some existing models largely under- or over-estimate 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 purely empirical models. It is found that the fit by some models is unacceptably high (e.g. error >20-30%). The results suggest that there are existing models which can predict the airflow resistivity of multi-component fibrous media with 12-20% error.

2.7 Analysis of acoustic properties of perpendicularly-laid nonwovens

This research presents a numerical investigation for acoustical properties of perpendicularly-laid nonwovens. The widely used impedance models such as Delany-Bazley, Miki, Garai-Pompoli and Komatsu models were used to predict acoustical properties. Comparison between measured and predicted values has been performed to get the most acceptable model for perpendicularly-laid nonwovens. It is shown that Delany-Bazley and Miki models can accurately predict surface impedance of perpendicularly-laid nonwovens, but Komatsu model has inaccuracy in prediction especially at low-frequency band. The results indicate that Miki model is the most acceptable method to predict the sound absorption coefficient with mean absolute error 8.39% from all the samples. The values are 8.92%, 12.58% and 69.67% for Delany-Bazley, Garai-Pompoli and Komatsu models, respectively.

3 Overview of the current state of the problem

The energy lost happens when sound propagates in small spaces, such as the interconnected pores of a porous absorber. This is primarily due to viscous boundary layer effects. There is also a loss in momentum due to changes in flow as the sound moves through the irregular pores. The boundary layer in air at audible frequencies is sub-millimeter in size, and consequently viscous losses occur in a small air layer adjacent to the pore walls. As well as viscous effects, there will be losses due to thermal conduction from the air to the absorber material; this is more significant at low frequency. Losses due to vibrations of the material are usually less important than the absorption as sound moves through the pores.[3] Sound-absorbing materials can absorb most of the sound energy (e.g. > 80%). Sound-absorbing materials contain a wide range of different materials; their absorption properties depend on frequency, porosity, density, thickness, airflow resistivity, composition, surface finish, and method of mounting. However, materials that have a high value of sound absorption coefficient are usually porous.[11-12] Most of the porous sound-absorbing materials commercially available are fibrous. Fibrous materials are composed of a set of fibers which can trap air between them. Fibrous materials made from polymers are used mostly for sound absorption and thermal isolation. Synthetic fibers are made through high-temperature extrusion and are based on nonrecoverable chemicals, often from petrochemical sources, their carbon footprints are quite significant.

Generally, fibrous sound-absorbing materials are used in the automotive industry to reduce interior noise and vibration and improve the sensation of ride comfort for the passengers. The use of fibrous sound-absorbing materials in vehicles is not only dependent on their acoustic properties but also on additional characteristics, such as thermal properties, compression properties and air permeability. Fibrous sound-absorbing materials applied to reduce noise and vibrations are used either individually or as components of complex composite materials which are an interesting area of research.[13] Physical properties of fibrous materials such as fiber type, fiber size, material thickness, density, airflow resistance and porosity can affect the acoustic properties.

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. 14-15. These models can be grouped into two main categories: theoretical models and empirical models. There are two main theories in airflow resistivity theoretical models: capillary channel theory and drag force theory. When modelling the acoustical behavior of porous materials, non-acoustic parameters such as porosity, airflow resistivity, tortuosity, thermal permeability and viscous and thermal characteristic lengths are tiring and time consuming to determine. The presently widely used sound absorption prediction methods are based on the theory proposed by Zwikker and Kosten.[16] In their theory, the surface characteristic impedance of rigidly-backed layer of porous material with finite thickness can be calculated by using characteristic impedance, complex wavenumber, and material thickness. Then, the normal-incidence sound absorption coefficient can be derived from the surface characteristic impedance.

4 Methods used, Studied Materials

In this study, five perpendicularly-laid nonwoven fabrics prepared by vibrating perpendicular lapper at the Technical University of Liberec, Czech Republic, as well as two types of commercial available nonwoven fabrics which separately made by vibrating perpendicular lapper and rotating perpendicular lapper were selected. The fiber layer of perpendicularly-laid nonwoven is bonded by melt-bonding fibers when it passes through the thermobonding chamber of vibrating and rotating perpendicular lappers.[17] The perpendicularly-laid nonwoven samples were made by different types of polyester fibers, they are PET, hollow PET and bicomponent PET. Three type of samples have same fiber content, while rest of four types of samples have another fiber content. The sheath part of bicomponent fibers are low-melting polyethylene terephthalate (PET). In order to get the cross-sectional slice of fibers, the resin embedding technology was utilized. Cross sectional and longitudinal microscopic images were also captured (see in Figure 1) at the Technical University of Liberec using JENAPOL microscope and NIS-elements software.

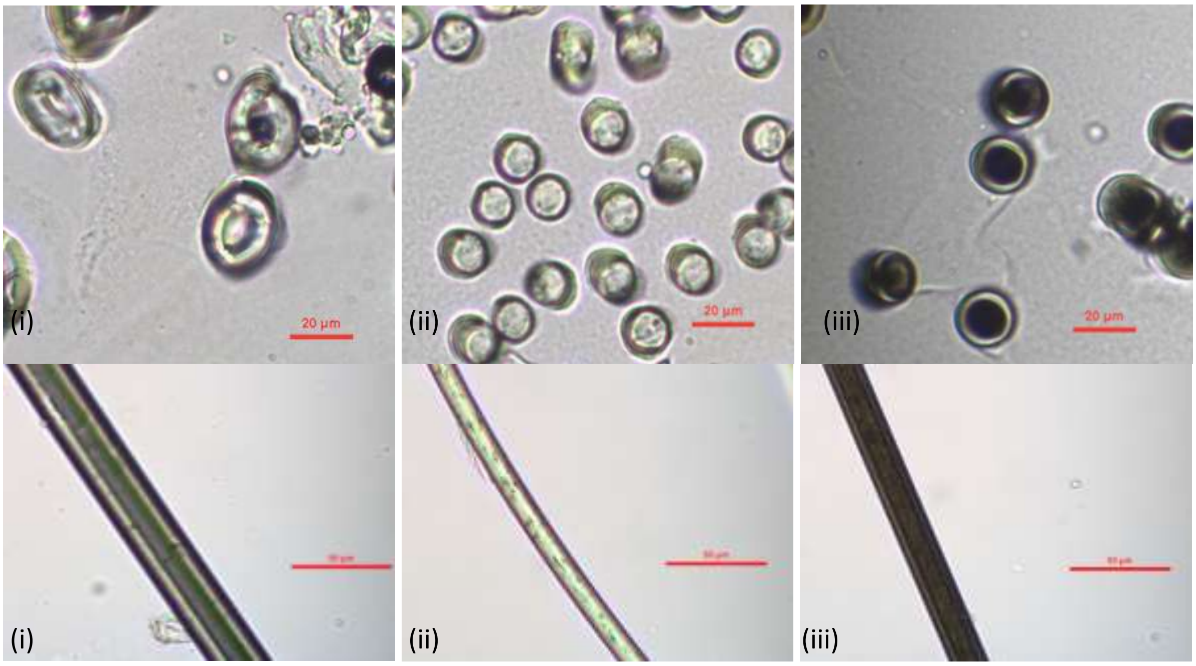

Figure 1 Cross-sectional and longitudinal microscopic images of polyester fibers: (i) hollow PET; (ii) PET; (iii) bi-component PET

In order to produce nonwoven samples with different thicknesses, the heat-pressing method was applied. Three types of samples were compressed under 600 Pa pressure at 130 ℃ for 5 minutes, thickness gauges were applied to obtain sample at certain thicknesses.

Besides perpendicularly-laid nonwoven fabrics, 50:50 ratio compositions of polyester/polyethylene thermal-bounded nonwoven fabrics embedded with aerogel were selected to carry out the study of the acoustic properties of aerogel based nonwoven fabrics. Aerogel was discovered more than 80 years ago. Aerogels have high porosity (>90%), a high specific surface area, low weight, and low sound velocity.[18-19] Due to these characteristics, aerogels can be used in sound absorption and thermal insulation fields. The type of aerogel used was hydrophobic amorphous silica aerogel, which is excellent for ambient and sub-ambient insulating applications.[20]

4.1 Evaluation of sound absorption

Acoustic properties of materials can be evaluated by steady-state methods, reverberant chamber methods, impedance tube methods, etc. In this study, the impedance tube was used to obtain normal incidence impedance.

Figure 2 Brüel and Kjær measuring instrument

A Brüel and Kjær measuring instrument (as shown in Figure 2) containing Type 4206 Impedance Tube, PULSE Analyzer Type 3560, and Type 7758 Material Test Software was used for sound absorption testing within the frequency range 50Hz–6.4 kHz. A large tube (100 mm in diameter) and a small tube (29 mm in diameter) were set up for measuring the sound absorption in low-frequency range from 50-1600Hz and high-frequency range 500-6400Hz respectively. The curves from both measurements were merged. The sound absorption values of lower common frequencies (start from 50 to 1600 Hz) were mainly from the large tube and the higher common frequencies (up to 1600 Hz) were mainly from the small tube.[8] The lower boundary was chosen higher than the tube limit in order to avoid inaccuracies caused by structural vibrations or phase mismatch.[21] The sound absorption coefficient measurements were carried out by using Brüel and Kjær measuring instrument at Technical University of Liberec.

Figure 3 Materiacustica 45 mm impedance tube

The surface impedance of perpendicularly-laid nonwovens was determined according to ISO 10534-2.[22] The 45 mm impedance tube manufactured by Materiacustica (as shown in Figure

3) was applied to carry out the impedance measurements. The measurement frequency range starts from 200 and goes up to 4200 Hz. The measurements of impedance were carried in the Jonas Lab at the University of Sheffield. For each nonwoven fabric, ten samples were measured.

4.2 Measurement of thermal properties

Alambeta instrument was used to measure thermal conductivity and thermal resistance, according to EN 31092 standard. The measuring head of the Alambeta contains a copper block which is electrically heated to approximately 32℃ to simulate human skin temperature, which is maintained by a thermometer connected to the regulator. The lower part of the heated block is equipped with a direct heat flow sensor which measures the thermal drop between the surfaces of a very thin, non-metallic plate using a multiple differential micro-thermocouple.[23] Each specimen was tested five times and the results were averaged.

4.3 Measurement of compression properties

The compression energy and compression load of perpendicularly-laid nonwovens were carried out by using a universal testing machine (TIRATEST 2300). Circular perpendicularly-laid nonwoven samples of diameter 10 cm were prepared. The compression tests were conducted at the velocity of 10 mm/min according to the ASTM D575-91 (Standard Test Methods for Rubber Properties in Compression). All the nonwoven specimens were compressed up to a deformation 90% of the initial thickness in an atmospheric condition of 20 ℃ and 65% relative humidity. Five tests were carried out for each sample. The fiber orientation angle at different compression stages was analyzed.

4.4 Measurement of air permeability

Air permeability measures the ability of a porous medium to transmit fluids. It depends on the porous geometrical structure.[24] The air permeability of perpendicularly-laid nonwovens were measured using FX3300 Textech Air Permeability Tester (Figure 4). The fabric sample is fixed as an obstacle in a flow of air by the clamping holder. A pressure difference Δp between both sides of the fabric sample develops as a consequence of hydraulic losses. The pressure difference is recorded by using of the manometer. The measured value is a speed of air in meter per second or a volume rate of the flow in liter per hour.

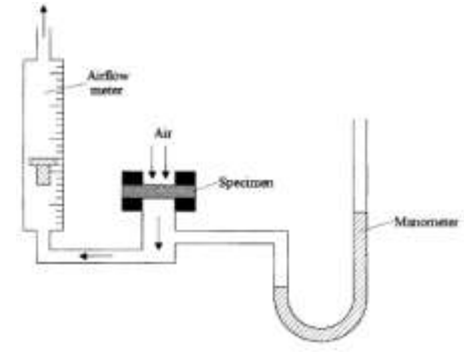

Figure 4 Set-up for measuring air permeability

4.5 Measurement of airflow resistivity

100 mm diameter circular shape samples were cut with an ELEKTRONISCHE STANZMASCHINE TYPE 208 machine to measure the airflow resistivity using a standard setup. In the present study, the airflow resistivity was measured with an AFD300 AcoustiFlow device (The Gesellschaft für Akustikforschung Dresden mbH, Dresden, Germany) according to ISO 9053:1991.[25] The measurement device is presented in Figure 5. Ten samples were measured for each perpendicularly-laid nonwoven fabric to study the reproducibility of the airflow resistivity experiment and scattering in the obtained data.

Figure 5 AFD300 AcousticFlow device

In the measurement process, the device generates different rate of airflow. Then, the pressure drop between two sides will be measured. The airflow resistance ($= \Delta P/u$) can be calculated from pressure drop and rate of airflow. Various pressure drop under different rate of airflow will be determined used to get the airflow resistance at 0.5 mm/s using linear regression method. The airflow resistivity will be obtained by dividing material thickness to the airflow resistance at 0.5 mm/s.

4.6 Statistical analysis

Statistical analysis software, Origin 8.5 and Matlab_R2017a were used to conduct all the statistical tests mentioned in this work. All of the statistical analysis work related to airflow resistivity and surface impedance models were well done in Matlab_R2017a. Power-model was used to get the most suitable empirical model for airflow resistivity of perpendicularly-laid nonwoven fabrics in the Matlab_R2017a software.

In order to numerically investigate the effect of perpendicularly-laid nonwoven fabric structure properties on the sound absorption ability, the noise reduction coefficient (NRC) and average value of SAC ($\bar{\alpha}$) of all the nonwovens were calculated. The NRC has been calculated as the average value of measured values for 250, 500, 1000 and 2000 Hz, which provides a decent and simple quantification of how well the porous material will absorb the noise. The $\bar{\alpha}$ is the average of the SAC for the whole sound absorption coefficient measurement range. The NRC of perpendicular nonwovens were calculated using the following equations:

$$NRC = \frac{\alpha_{250Hz}+\alpha_{500Hz}+\alpha_{1000Hz}+\alpha_{2000Hz}}{4} \quad (1)$$

During the impedance tube measurement process, the sound absorption coefficient was measured at even number of frequency in the range of 2 to 6400 Hz. The values of sound absorption coefficient are not accurate under 100 Hz, so the $\bar{\alpha}$ was calculated from 50 to 6400 Hz. The equation for calculating $\bar{\alpha}$ is as follows:

$$\bar{\alpha} = \frac{\int_{F_1}^{F_2} \alpha(f) df}{F_2 - F_1} \tag{2}$$

where F_1 (50 Hz) is lower bound of sound frequency in testing and F_2 (6400 Hz) is upper bound of sound frequency in measurement.[26]

For investigation of the accuracy of airflow resistivity models, the mean absolute values of relative error (MAVRE) was calculated according to the following equation:

$$\Delta = \frac{\sum_{n=1}^{N} \Delta_n}{N} = \frac{1}{N} \sum_{n=1}^{N} \frac{|\sigma_{p,n} - \sigma_{m,n}|}{\sigma_{m,n}} , \tag{3}$$

where σ_p is the predicted airflow resistivity, σ_m is the measured airflow resistivity, and N is the total number of material specimens studied (N=18). A MAVRE of 0.2 means a difference of 20% from the measured value.

A similar method for comparison between measured and predicted airflow resistivity was used to analyze the prediction errors of sound absorption coefficient among the four models. The MAVRE for sound absorption prediction were calculated according to the following equation:

$$error = \frac{|\sum \alpha_{meas} - \sum \alpha_{pred}|}{\sum \alpha_{meas}} \times 100\% , \tag{4}$$

where α_{meas} is the measured absorption coefficient, and α_{pred} is the predicted value.

5 Summary of the results achieved

5.1 Sound absorption properties of perpendicularly-laid nonwovens

The sound absorption coefficient SAC (α) indicates how much of the sound is absorbed in the material. When sound wave propagate into a media part of input sound energy W_i [J] is transform into heat (W_q [J]), part is reflected back (W_r [J]) and part is transmitted through insulation layer (W_t [J]). The sound absorption coefficient SAC (α) can be defined as:

$$\alpha = 1 - \frac{W_r}{W_i} = \frac{W_q + W_t}{W_i} \,. \tag{5}$$

The normal incidence sound absorption coefficient of perpendicularly-laid nonwovens was determined as a function of the sound frequency. The normal incidence SAC of part of the perpendicularly-laid nonwoven samples was measured by using Brüel and Kjær impedance tube (as shown in Figure 2). The Brüel and Kjær impedance tube contains a large tube (100 mm in diameter) and a small tube (29 mm in diameter) which used to obtain the sound absorption coefficient in low-frequency range from 50-1600Hz and high-frequency range 500-6400Hz respectively. Later the measurement data from large and small tube were combined to form the curves for the frequency range between 50-6400 Hz. The normal incidence sound absorption coefficient of original perpendicularly-laid nonwovens is shown in Figure 6.

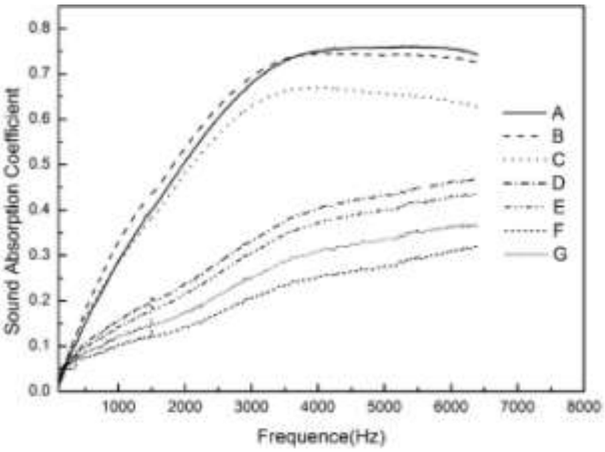

Figure 6 Sound absorption coefficient of original perpendicularly-laid nonwovens

It is observed that sound absorption coefficient of the test samples lies in the range of 0.017-0.76. Apparently, the value of absorption coefficient for samples A, B and C sharply increases at frequency bands 50 Hz-3500 Hz and the maximum value of absorption coefficient occurs at frequency bands 4000 Hz-5400 Hz. However, samples D, E, F and G show lower absorption coefficient value in comparison to samples A, B and C, and the value of absorption coefficient increases with the increasing of frequency at the whole measurable frequency bands (50Hz-6400 Hz). Results indicate that perpendicularly-laid nonwoven exhibits much better sound absorption ability at frequency bands 3000 Hz-6400 Hz.

Samples produced by different manufacturing techniques were measured for sound absorption performance and the results are shown in Figure 7. Sample A was produced by rotating perpendicular lapper (WAVEMAKER), and samples B and C were prepared by vibrating perpendicular lapper (PERPENDICULARLY-LAID). The manufacturing techniques, thicknesses and areal densities of samples are listed following sample codes. WAVEMAKER is rotating perpendicular lapper, STRUTO is vibrating perpendicular lapper, SAC is sound absorption coefficient. Samples A1, B1 and C2 were obtained from samples A, B and C through heat-pressing method. It is obviously found that all the samples SAC sharply rise with the increasing frequency, but the curves turn to be flat after around 3500 Hz. From Figure 7(a), it can be seen that sample B exhibits the highest SAC at low-frequency band, but after 3500 Hz sample A shows better sound absorption ability. Meanwhile, sample C shows the lowest SAC after 1000 Hz compared to samples B and C. In Figure 7(b), sample A exhibits the best sound absorption ability while sample C shows the lowest SAC. It is found that samples with higher areal density have better sound absorption performance, and samples with lower areal density are weaker absorbers. The reason for this phenomenon can be samples thickness and areal density differences.[27-28]

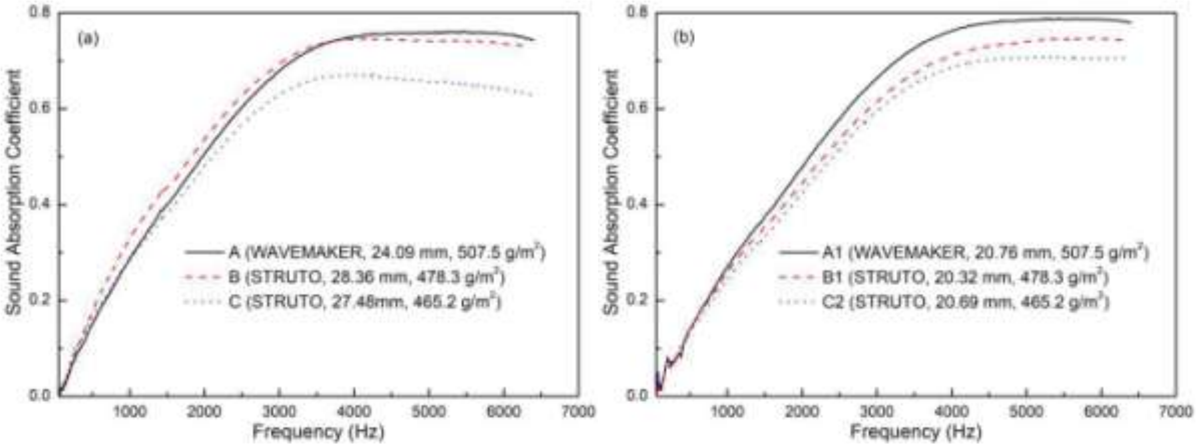

Figure 7 SAC of samples produced by different manufacturing techniques: (a) SAC of original samples; (b) SAC of samples prepared by the heat-pressing method from original samples

Nonwoven thickness is a very important factor determining the sound absorption ability. Generally, the increase of thickness results in an increase of sound absorption coefficient at low-frequency range. Moreover, the sound absorption of fibrous material involves viscous losses, which convert acoustic energy into heat as sound wave travels through the interconnected pores of fibers of the material. Thus, for high areal density samples there are more fibers involved in the viscous losses and more acoustic energy is dissipated in the form of heat energy.[28] In the case of similar thickness, the increase of fabric areal density leads to an increase in sound absorption performance. Based on above analysis, by comparing SAC of samples A, B, C, A1, B1 and C2, it is hard to conclude that samples produced by rotating perpendicular lapper have better sound absorption performance.

The NRC and computed $\bar{\alpha}$ values for the perpendicularly-laid nonwovens are listed in Table 1. In order to investigate the effect of areal density on sound absorption performance of perpendicularly-laid nonwovens, seven types of nonwoven samples with similar thickness were compared in Figure 8.

Table 1 $\overline{\alpha}$ and NRC of perpendicularly-laid nonwovens

Sample codes	$\overline{\alpha}$		NRC	
	Mean value	95% confidence interval	Mean value	95% confidence interval
A	0.580	0.58 ± 0.00789	0.254	0.254 ± 0.00263
A1	0.581	0.581 ± 0.00614	0.239	0.239 ± 0.00351
B	0.588	0.588 ± 0.00614	0.281	0.281 ± 0.00263
B1	0.545	0.545 ± 0.0105	0.228	0.228 ± 0.00438
C	0.523	0.523 ± 0.00526	0.255	0.255 ± 0.00438
C1	0.544	0.544 ± 0.00526	0.242	0.242 ± 0.00175
C2	0.521	0.521 ± 0.00438	0.216	0.216 ± 0.00263
C3	0.528	0.528 ± 0.00701	0.191	0.191 ± 0.00263
C4	0.433	0.433 ± 0.0131	0.147	0.147 ± 0.00438
C5	0.444	0.444 ± 0.0245	0.136	0.136 ± 0.00526
D	0.315	0.315 ± 0.0245	0.142	0.142 ± 0.00877
E	0.290	0.29 ± 0.0149	0.129	0.129 ± 0.00526
F	0.201	0.201 ± 0.00614	0.092	0.092 ± 0.00351
G	0.242	0.242 ± 0.0123	0.110	0.11 ± 0.00438

$\bar{\alpha}$: average value of sound absorption coefficient; NRC: noise reduction coefficient.

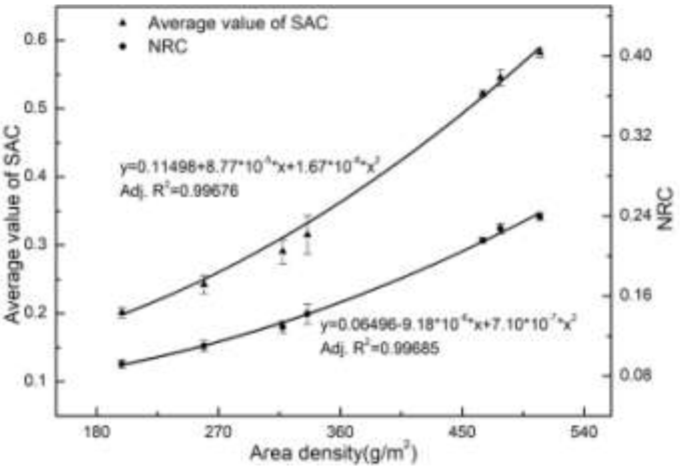

Figure 8 Effect of areal density on sound absorption performance

It is found that the sound absorption performance shows similar trend as samples areal density. It means that the sound absorption ability of similar thickness perpendicularly-laid nonwovens increase with an increase of samples areal density or bulk density. In the case of similar thickness, the increase of fabric areal density leads to an increase in sound absorption performance. This phenomenon can be seen in Figure 8, both NRC and average value of SAC increase with the increase of areal density. It is also observed that the NRC and average value of SAC have a strong quadratic correlation with areal density: the adjusted coefficients of determination (R^2) are 0.99676 and 0.99685, respectively. It can be concluded that higher areal density gives better sound absorption ability for perpendicularly-laid nonwovens when materials have similar thickness.

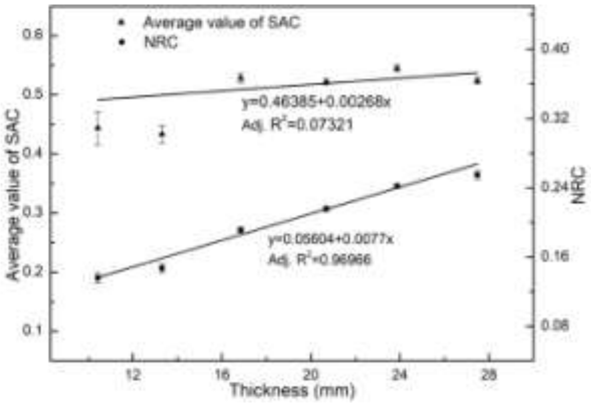

Figure 9 Effect of thickness on sound absorption performance

The effect of thickness on the sound absorption performance is presented in Figure 9. The adjusted coefficients of determination between the NRC and thickness is 0.96966, and this value is 0.073 for average value of SAC and thickness, indicating that the NRC of perpendicularly-laid nonwovens has a very strong correlation with thickness while an insignificant relationship between average value of SAC and thickness. As described above, the increase of thickness results in SAC increases at low-frequency bands while SAC decrease at high-frequency bands. Meanwhile, NRC was defined as material's sound absorption ability at low frequency and average value of SAC was described as sound absorption ability for whole measurement frequency. This can be the reason of this phenomenon.

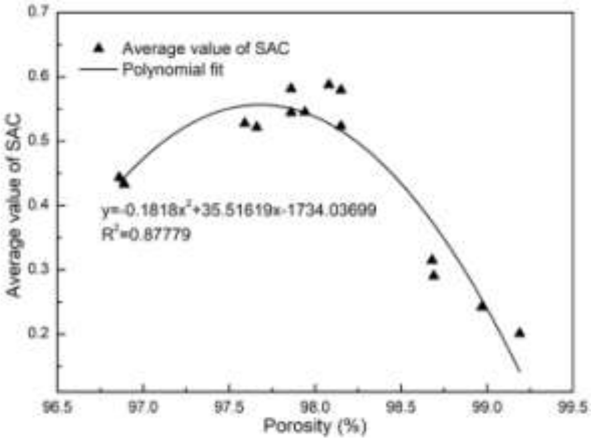

Figure 10 Effect of porosity on sound absorption performance

Porosity has a strong influence on sound absorption performance of fibrous materials. Figure 10 illustrates the effect of porosity on sound absorption performance of perpendicularly-laid nonwovens. It can be seen that the average value of SAC increases with the increase of porosity, the average value of SAC reached peak values between 97% and 98% of porosity, but average value of SAC sharply decreases after 98% of porosity. The porosity is inversely proportional to perpendicularly-laid nonwoven specific air flow resistance.[20] Lower porosity means higher specific air flow resistance, which means fiber movement rarely occurs when sound wave passes through the materials.[29] High porosity results in fewer number of fibers involved in the viscous losses, which will decrease the sound absorption performance of the materials. The quadratic correlation between porosity and average value of SAC was calculated and mentioned in Figure 10. It can be found that porosity has a quadratic relation with average value of sound absorption coefficient with adjusted coefficient of determination 0.87779.

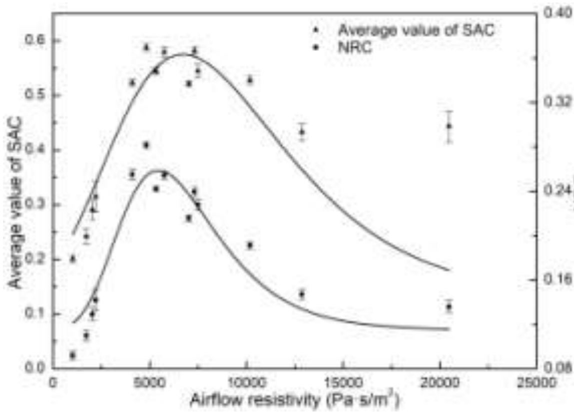

Figure 11 Effect of airflow resistivity on sound absorption performance

The airflow resistivity of a porous material is one of the most important defining characteristics. In order to investigate the influence of airflow resistivity on sound absorption performance in a simple way, the correlation between them has been illustrated in Figure 11. It is found that below 6000 Pa•s/m² with the increase of airflow resistivity the sound absorption ability increases as well. The highest value of both average value of SAC and NRC appeared at the range between 5000 and 7000 Pa•s/m² of airflow resistivity. After that, the sound absorption ability shows a decrease trend with the increasing of airflow resistivity. This phenomenon is completely compatible to Zent and Long's research.[27]

5.2 Sound absorption properties of aerogel based nonwovens

The sound absorption coefficient (SAC) of single layer aerogel based nonwoven fabrics is shown in Figure 12. It is observed that the SAC of samples A, B and C increase with the increase of frequency. In addition, the SAC of all samples A, B and C exhibit a steady increase at the whole measurable frequency bands (50-6400 Hz). Single layer of sample C shows the best sound absorption ability in whole test band. SAC of samples A, B and C attain peak values at 6400 Hz, the maximum values are 0.385, 0.766 and 0.832, respectively.

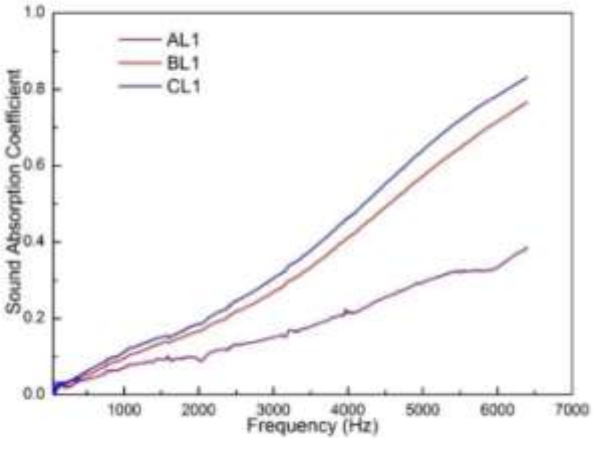

Figure 12 Sound absorption coefficients of single layer aerogel based nonwoven fabrics

Table 2 Noise reduction coefficient (NRC) of single layer aerogel based nonwoven fabrics

Samples	Sample codes	Mean value	95% confidence interval
AP-A	AL1	0.0556	0.0556 ± 0.000789
AP-B	BL1	0.0862	0.0862 ± 0.00263
AP-C	CL1	0.0977	0.0862 ± 0.00263

The NRC of aerogel based nonwoven fabrics was calculated using the Eq. 1. The NRC for single layer aerogel based nonwovens are listed in Table 2. The NRC is a dimensionless number. The NRC values of single layer aerogel based nonwoven fabrics are found to lie in the range of 0.0556-0.0858, indicating that single layer aerogel based nonwoven fabrics are not effective absorbers for low-frequency sound absorption. It is also observed that sample C exhibits higher sound absorption ability, superior to samples A and B although sample C has lowest aerogel content. It indicates that aerogel content is not a crucial factor in determining the sound absorption ability compared to the thickness and density.

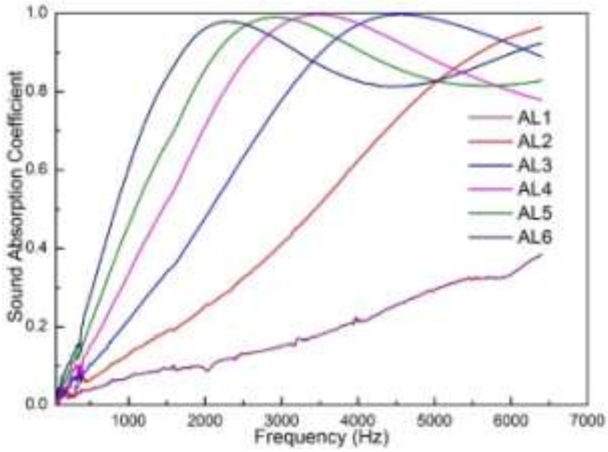

Figure 13 SAC of multilayered aerogel based nonwoven fabric A

The SAC of multilayered sample A is shown in Figure 13. It is found that two layers of sample A have a significant improvement in the sound absorption ability in the whole measurable frequency bands. It is also observed that as the thickness increased, the SAC at low frequencies increased as well. However, the SAC decreased at high frequencies after two layers, and the peaks of SAC curves shift towards the lower frequency side.

5.3 Some airflow resistivity models for multi-component polyester fiber assembly

The fiber diameter is one of the key parameters to predict the airflow resistivity with a theoretical model. The ImageJ software based on the scanning electron microscope (SEM) images (see Figure 14) to measure the fiber diameter, so that the fiber diameter distribution for polyester nonwovens were obtained. 2358 fiber diameters from 150 SEM images were measured in total to ensure reproducible statistics. The result of fiber mean diameter is 15.94 μm.

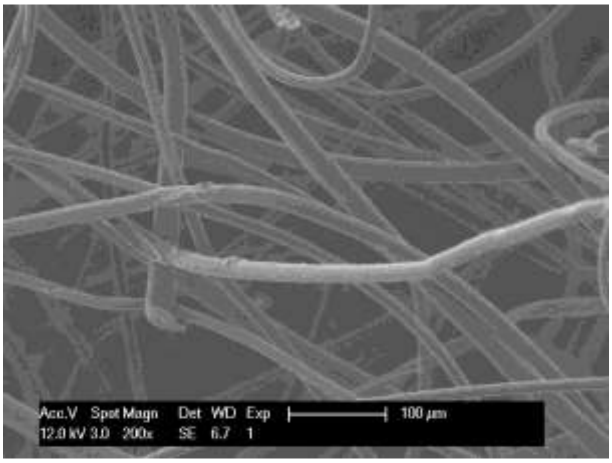

Figure 14 The scanning electron microscope (SEM) image of sample A

The accuracy of theoretical and empirical models was investigated by comparing the relative prediction errors. The mean absolute values of relative error (MAVRE) was calculated according to the Eq. 3.

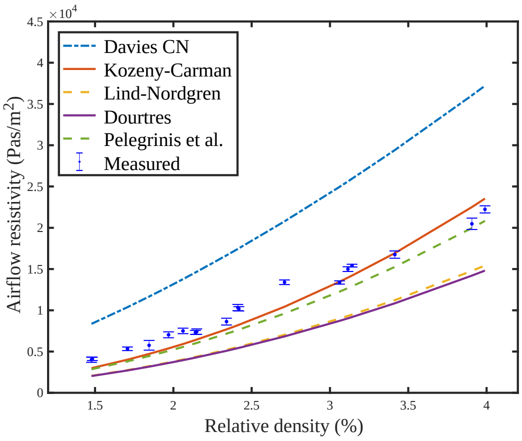

Figure 15 Predicted airflow resistivity based on capillary channel theory

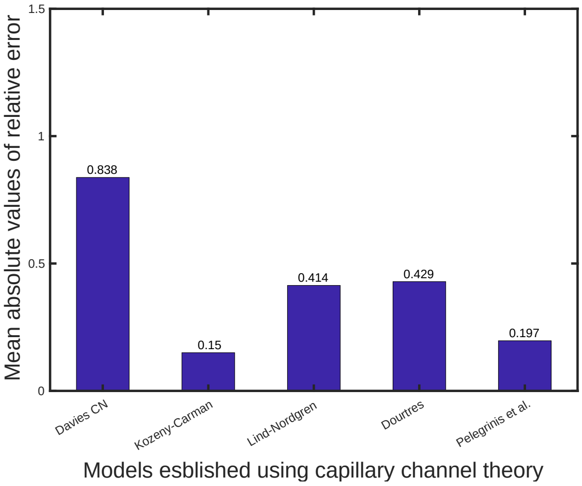

Figure 16 The MAVRE of airflow resistivity based on capillary channel theory

The predicted airflow resistivity values based on capillary channel theory are show in Figure 15 as a function of the relative density. The mean absolute values of relative error (MAVRE) of capillary channel theory models are compared in Figure 16. It can be seen that Doutres and Lind-Nordgren models predict similar values of the airflow resistivity. The Kozeny-Carman model agrees closely with that by Pelegrinis *et al*. This difference can be explained by the fact that the two sets of models make use of rather different coefficients in the flow resistivity equations: 180 for the Kozeny-Carman type models; and 128 for the Lind-Nordgren models. This difference in the predicted airflow resistivity increases proportional to the material density. The Davies CN model shows the highest value of predicted airflow resistivity and a relatively high error. It is observed that the maximum MAVRE for this model is 83.8%. The MAVRE of Kozeny-Carman model, with a maximum value of 15% which is the lowest among the five models considered. The maximum error for the Pelegrinis *et al.* model is relatively low which is 19.7%. It was also found that the Kozeny-Carman model is more reliable when the material density is relatively low. However, it begins to overestimate the airflow resistivity as the relative less than 4%.

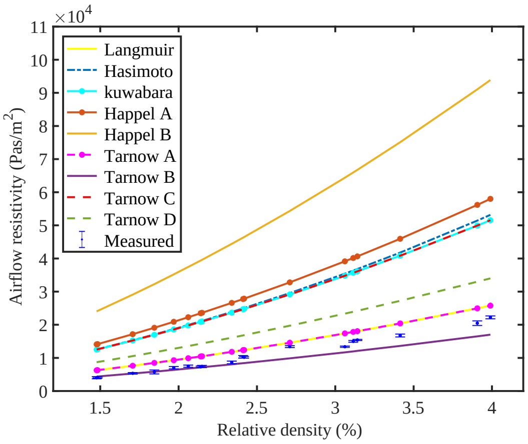

Figure 17 Predicted airflow resistivity based on drag force theory

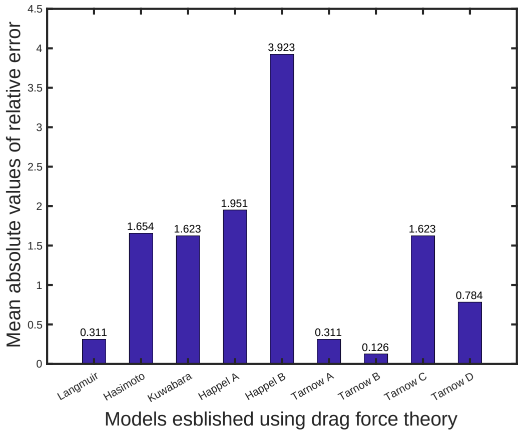

Figure 18 The MARVE of airflow resistivity based on drag force theory

The calculated airflow resistivity of multi-component polyester materials based on the drag force theory is presented in Figure 17. Figure 18 presents the mean absolute values of relative error (MAVRE). The results presented in Figure 18 suggest that the model by Happel (Happel B model) for the airflow perpendicular to fibers significantly overestimate the resistivity by over 390%. The predictions by Hasimoto, Kuwabara, Happel A (airflow parallel to the fibers) and Tarnow C (airflow perpendicular to fibers arranged in the form of lattice) are very similar and overestimate the measured airflow resistivity by 160-200%. The predictions by the Langmuir and Tarnow A (airflow parallel to the fibers arranged in square lattice) are almost identical but overestimate the airflow resistivity by approximately 31.1%. The predictions by Tarnow D model (airflow is perpendicular to the fibers arranged in random lattice) fall between the two latter groups. The most accurate model for the flow resistivity of this kind of fibers is the Tarnow B model (airflow is parallel to fibers arranged in random lattice). This model is accurate within 13%. In addition, it can be seen that the Tarnow B model is more accurate when the materials have relatively low density, however this model exhibits higher variation comparing to measured values at high density range. This phenomenon can be explained by the decrease of fibrous layer orientation angle with increased density for high specimen compression as illustrated in Figure 17. When the fibrous layer orientation angle decreases, the airflow is no longer parallel to the fibers. When the orientation angle is close to 0 the airflow becomes perpendicular to the fibers. For these materials the measured flow resistivity (see Figure 17) is higher than that predicted with Tarnow B models which work better when the flow is parallel to the fibers.

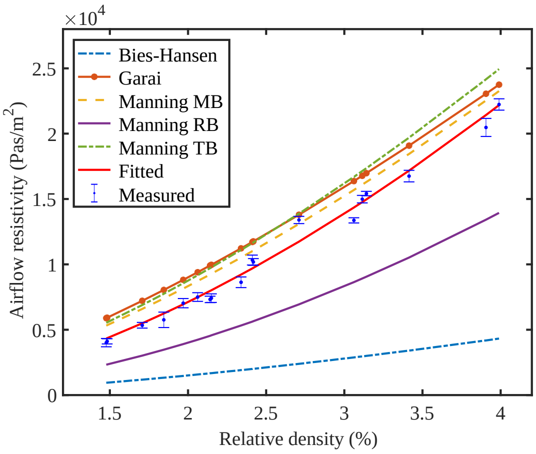

Figure 19 Predicted airflow resistivity based on empirical models

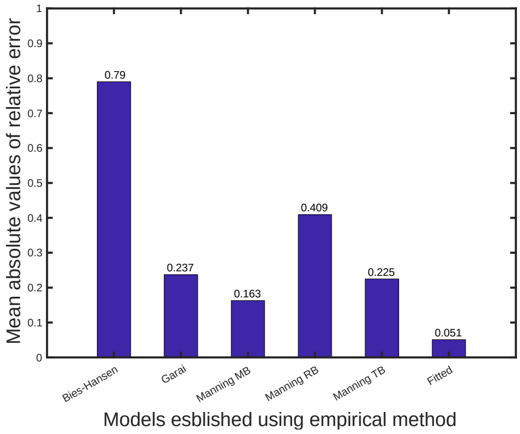

Figure 10 The MARVE of airflow resistivity based on empirical models

The predicted airflow resistivity calculated from empirical models are presented in Figure 19. Figure 20 presents the prediction MARVE data. The Bies-Hansen and Manning RB models give significantly underestimated airflow resistivity of multi-component polyester materials in comparison with measured values. This can be explained by the different materials and bonding method in their studies in comparison with in the current study.[30-31] Garai, Manning MB and TB models exhibit similar results and relative good agreement by comparing the measured airflow resistivity. It is observed that the MARVE for these three models range from 15.8% to 41.2%. The predictions by Manning TB and Garai are very close, but Manning TB method shows better predictions. The MARVE for Manning RB/TB and Garai models increase with the increased value of the relative density. The relative error for these models is below 10% when the relative density of the fibrous material is below 3%.

$$\sigma = \frac{1.053\times10^{-8}\times\rho^{1.645}}{d^2} \tag{6}$$

Although one drag force theory model exhibits acceptable prediction for multi-component polyester nonwovens, the the empirical models are not reliable which overestimate the airflow resistivity by 16%. One same type simple empirical model was developed by power-fitting the values of measured resistivity, the model presented in equation 6. The fitted empirical model is show in Figure 19 - 20. The relative prediction error of the fitted empirical model is 5.1%.

5.4 Numerical analysis of acoustic properties of perpendicularly-laid nonwovens

This section presented four commonly used impedance models, such as Delany-Bazley, Miki, Garai-Pompoli and Komatsu models. The effect of surface morphology on an acoustic wave can be characterized by four interrelated acoustic quantities: impedance, admittance, pressure reflection coefficient and absorption coefficient. The impedance, admittance and pressure reflection coefficient describe the magnitude and phase change on reflection. The surface impedance contains real part (resistance) and imaginary part (reactance). The real part of surface impedance is associated with energy changes, and the imaginary part with phase changes. Thus, the surface acoustic impedance gives more insight information about the absorbing properties of a material than the absorption coefficient. The predicted surface impedance and absorption coefficient will be demonstrated in this section. In addition, the accuracy between predicted and measured absorption coefficient will be presented.

One sample with 5757 Pa·s/m² airflow resistivity was chosen to figure out the most suitable model for impedance prediction of multi-component polyester nonwoven. Figure 21 demonstrates the comparisons of normalized impedance between the measured values and the values calculated using the Delany–Bazley model, the Miki model, the Garai-Pompoli and the Komstsu model. The normalized surface impedance is the ratio of surface impedance to the characteristic impedance of air ($Z_s/\rho_0 c_0$). It can be seen that Delany-Bazley and Miki model have accurate predictions on normalized surface impedance, while Komatsu model exhibits significant difference compared to measured values especially at low to mid frequency range. The reason for the inaccuracy of Komatsu method can be attributed to the wider airflow resistivity range (i.e. 6000 - 72900 Pa·s/m²) used to derive the impedance prediction equations compared with the range from 4108 to 20474 Pa·s/m² in this study.

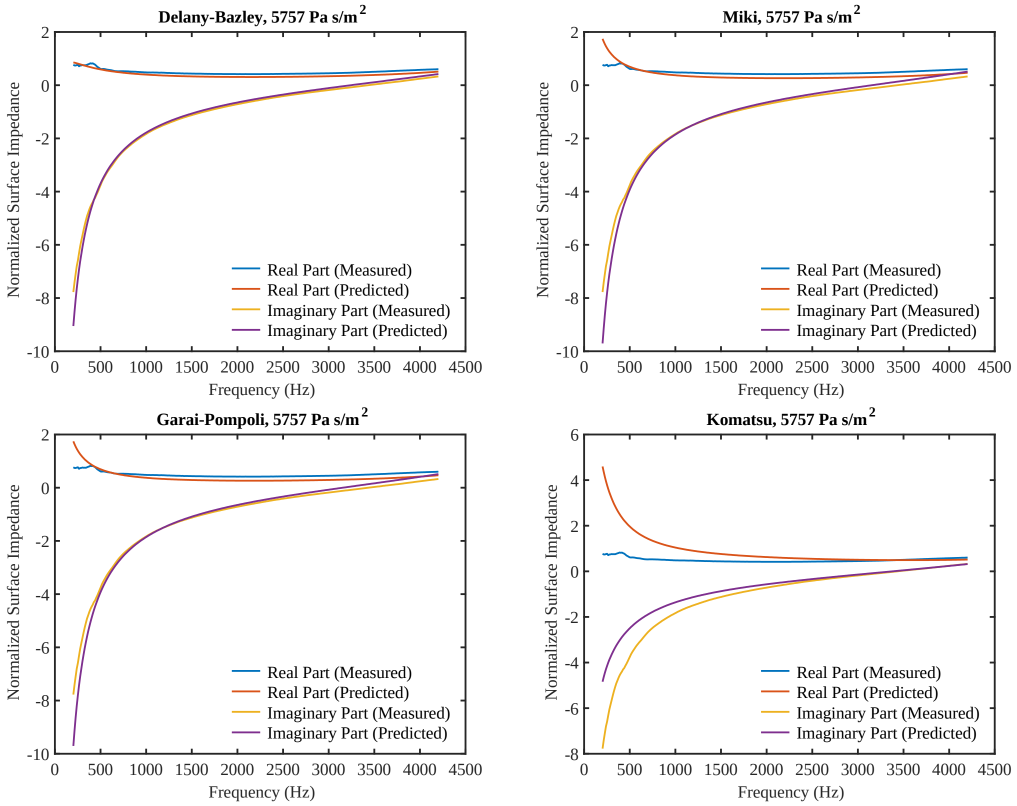

Figure 11 Measured and predicted impedance for the sample with airflow resistivity of 5757 Pa·s/m²

In order to clearly show the adaptability of the models for multi-component polyester nonwovens, the MAVRE of Komatsu model was separately presented in Figure 22. The MAVRE based on Delany-Bazley model, Miki model and Garai-Pompoli model were shown in Figure 23. The Komatsu model exhibits the highest MAVRE of 125% for the sample with 12868 Pa·s/m² airflow resistivity. MAVRE is relatively low when the resistivity is small. The Komatsu method shows around 70% mean MAVRE, while the values from other three methods are less than 15%. From Figure 23, it is found that Delany–Bazley model and Miki model have similar results. The difference on their mean MAVRE is less than 0.6% which are 8.92% and 8.39%, respectively. However, it is obviously found that the absorption coefficient predicted by Miki model yields closer results for most of the samples than that from Delany-Bazley model. The MAVRE between the Delany-Bazley and Miki methods and measured values of the absorption coefficient are smaller than those between the Garai-Pompoli method and measured values.

It is considered that the results with an error less than 10% are accurate for this kind of analysis, as the value of bulk density and thickness for a fibrous material can vary due to several uncertainties during measurements. Uncertainties such as fabric compression, fiber density and any inaccuracy or noise that is present during the acquisition of the acoustical data might have resulted in erroneous data.[21] Thus, it can be concluded that the Delany-Bazley and Miki models are superior in terms of the sound absorption coefficient by comparing Garai-Pompoli and Komatsu models. It can also be concluded that Miki model can be used to accurately predict sound absorption coefficient of multi-component polyester nonwovens.

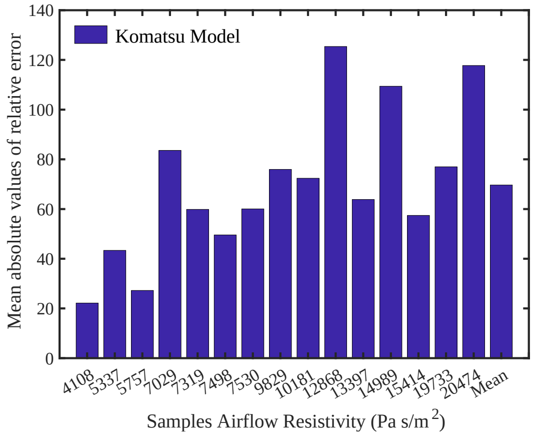

Figure 12 MAVRE based on Komatsu model. The airflow resistivity on horizontal axis represents corresponding samples

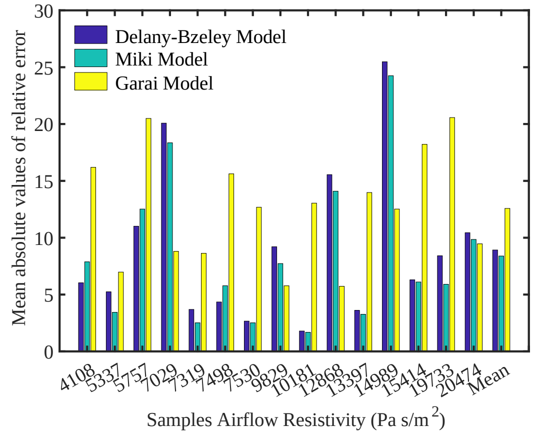

Figure 13 MAVRE based on Delany–Bazley model, Miki model and Garai-Pompoli model

5.5 Compression property of perpendicularly-laid nonwovens

The compression properties of all the perpendicularly-laid nonwovens are shown in Figure 24. The absorbed energy was computed by multiplying load pressure and thickness reduction of samples. It can be found that sample C5 exhibits highest compressional resistance at 50 % and 90 % thickness reduction, while sample C3 absorbs the highest energy during the compression test. In addition, sample F shows lowest compressional resistance and energy absorption of compression.

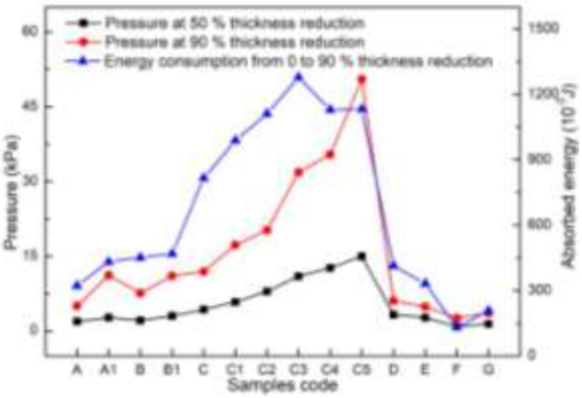

Figure 14 Compression properties of perpendicularly-laid nonwovens

Samples B1, D, E, F and G, with similar thickness, were prepared by vibrating perpendicular lapper. These samples were chosen to investigate the effect of density on compression property. From Figure 25, it can be seen that compressional resistance decreases with the increase of porosity. The compressional resistance of perpendicularly-laid nonwovens has a strong correlation with density, with an adjusted coefficients of determination of 0.97185, which means the perpendicularly-laid nonwovens with higher density usually exhibit better compression property.

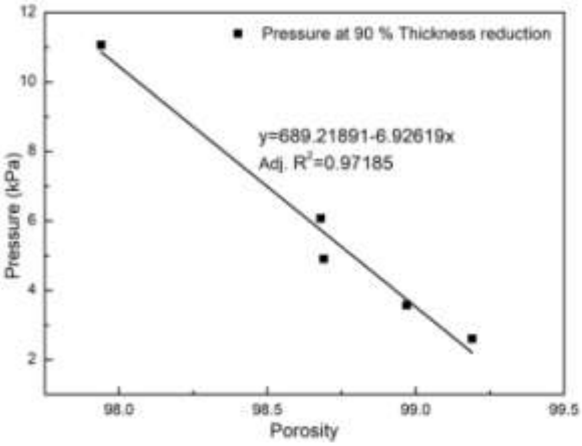

Figure 15 Effect of porosity on compression property

5.6 Thermal properties of perpendicularly-laid nonwovens

Thermal conductivity and thermal resistance of perpendicularly-laid nonwovens are presented in Figure 26. For nonwovens with approximately the same thickness (samples D, E, F and G), thermal resistance increases with the increasing of fabric areal density and thermal conductivity shows an adverse trend. This is because increase in areal density causes increase in fiber to fibre contact and packing density as well as tortuosity, so less heat flows through the channels in nonwoven, and thermal resistance therefore increases correspondingly. Moreover, for samples A, B and C, since they have slightly different areal density and varying thickness, the increase of thermal resistance with the increase in sample thickness indicated that fabric thickness plays a major role in deciding thermal resistance of perpendicularly-laid nonwovens.

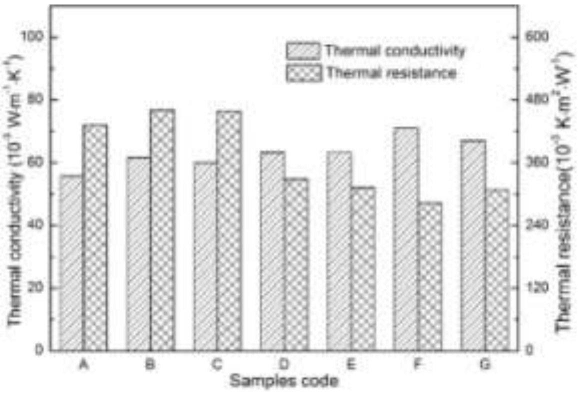

Figure 16 Thermal properties of perpendicularly-laid nonwovens

Nonwoven fabrics possess a large amount of void space, which can entrap large volumes of stagnant air. Resulted from the much lower conductivity of still air in comparison to textile fibres, the thermal insulation performance of nonwoven textiles is determined by the trapped air in the inter-fibre spaces. The effect of porosity on thermal properties of perpendicularly-laid nonwovens is illustrated in Figure 27. Results showed that the thermal properties of high-porous nonwovens have strong correlation with porosity. Especially, the thermal resistance is directly proportional to fabric porosity, with adjusted coefficients of determination 0.891, indicating that nonwovens with higher porosity usually exhibit better thermal insulation performance since they can preserve more still air.

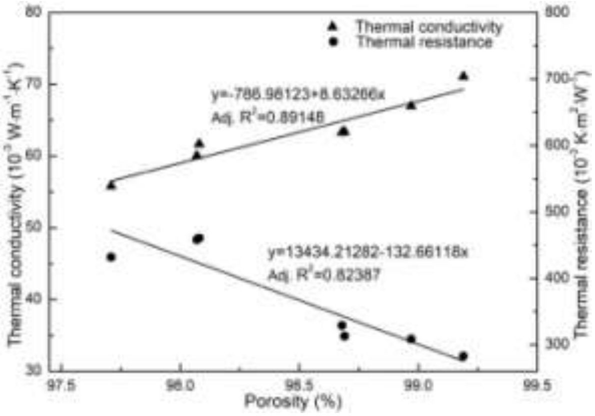

Figure 17 Effect of porosity on thermal properties

Since the fabric thickness, fiber fineness and fabric areal density are very important factors in determining both acoustic and thermal properties of perpendicularly-laid nonwovens, there appears a great interest to investigate the relationship between these two properties for perpendicularly-laid nonwovens.

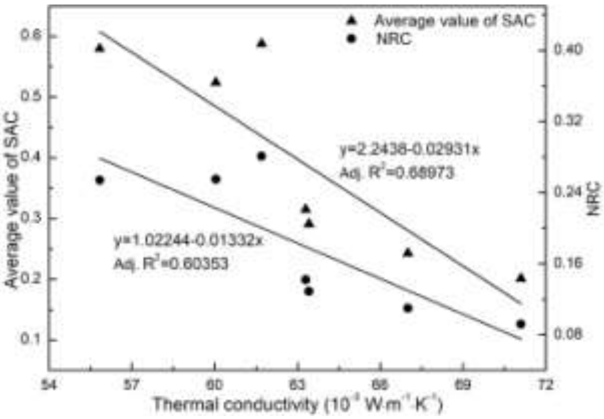

Figure 18 Estimation of correlation between thermal conductivity and sound absorption (NRC and average value of SAC)

Figure 28 illustrates the estimation of correlation between thermal conductivity of perpendicularly-laid nonwovens and sound absorption, NRC and average value of SAC ($\bar{\alpha}$). It is observed that both NRC and $\bar{\alpha}$ have insignificant correlation with thermal conductivity, the adjusted coefficients of determinations are 0.60353 and 0.68973, respectively. The reason could be that thermal conductivity is not dependent on fabric thickness while fabric thickness is a determining factor for sound absorption.

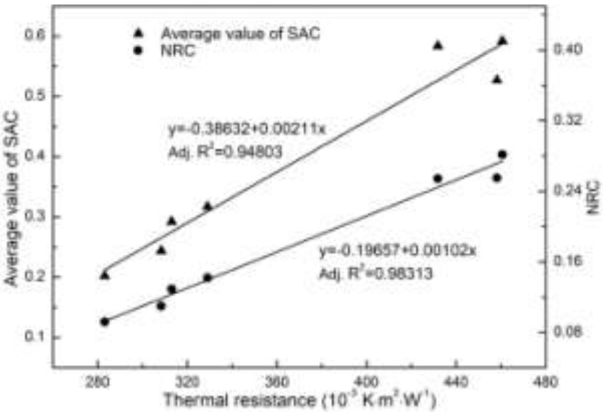

Figure 19 Estimation of correlation between thermal resistance and sound absorption (NRC and average value of SAC)

Estimation of correlation between thermal resistance and sound absorption, NRC and $\bar{\alpha}$, are presented in Figure 29. The adjusted coefficients of determination between NRC and thermal resistance is 0.98313, and this value is 0.94803 for $\bar{\alpha}$ and thermal resistance, indicating that the sound absorption performance of perpendicularly-laid nonwovens has a very strong correlation with thermal resistance. It can be concluded that NRC and $\bar{\alpha}$ are directly proportional to thermal resistance of perpendicularly-laid nonwovens. That means for different perpendicularly-laid nonwovens, a higher thermal resistance suggests a better sound absorption performance.

5.7 Air permeability of perpendicularly-laid nonwovens

As shown in Figure 30, the porosity of the material has a strong influence on the air permeability of the material. It is obvious that the increase in porosity leads to increase in air permeability. The quadratic correlations dependences between porosity and air permeability were also calculated and mentioned in Figure 30. It is found that porosity has a quadratic relation with air permeability with adjusted coefficients of determination 0.99261.

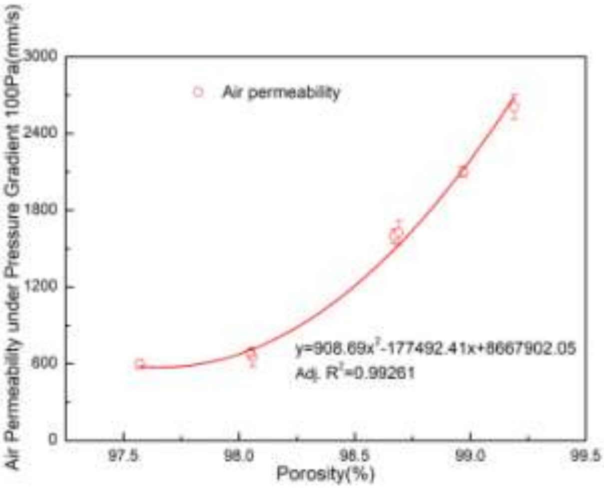

Figure 20 Effect of porosity on air permeability

Estimated correlation between air permeability and sound absorption is presented in Figure 31. It is observed that $\bar{\alpha}$ has significant correlation with air permeability, the adjusted coefficients of determination is about 0.98, indicating the existence of an inverse relation between air permeability and sound absorption of perpendicularly-laid nonwovens. That means perpendicularly-laid nonwoven with lower air permeability usually exhibits better sound absorption performance. This may provide a new method to evaluate the sound absorption property of perpendicularly-laid nonwovens by means of air permeability testing.

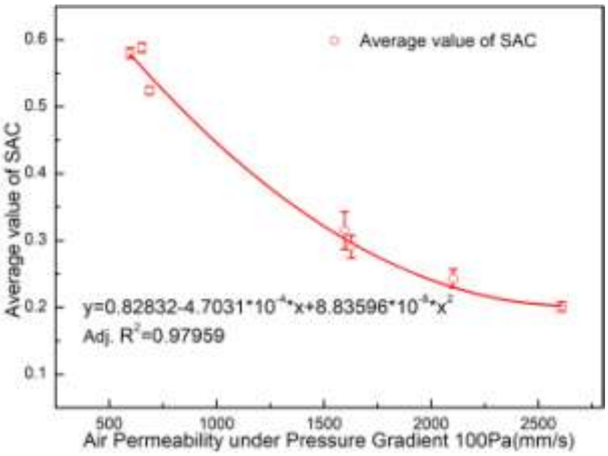

Figure 21 Estimated correlation between air permeability and sound absorption

6 Evaluation of results and new finding

In this study, the acoustic properties, airflow resistivity, compressibility, thermal properties and air permeability of perpendicularly-laid nonwovens were investigated. Besides, the sound absorption properties of aerogel based nonwovens have been analyzed.

It is found that there is no significant influence of two manufacturing techniques on sound absorption performance. The increase of areal density results in improvement of sound absorption ability. The increase of thickness can improve sound absorption coefficient at low-frequency range, but decrease of the coefficient occurred at high-frequency range. A quadratic relationship between porosity and sound absorption ability has been found.

An investigation on sound absorption performance of aerogel based nonwoven fabrics was carried in this study. The results show that there is a decrease in SAC with the increase of aerogel content. It is observed that the noise reduction coefficient (NRC) linearly increased with the increase of layers for all the samples. It was also found that the air-back cavities result in resonance phenomenon, as the increase in thickness of air-back cavities the peak values of SAC shift towards lower frequencies.

This study 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 fiber diameter information. 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. It is found that the mean absolute values of relative error (MAVRE) 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 12.6% accuracy. A simple empirical model based on fiber diameter and fabric bulk density has been obtained through power-type model. This model exhibits very small error which is 5.1%.

The widely used impedance models such as Delany-Bazley, Miki, Garai-Pompoli and Komatsu models were used to predict acoustical properties. It is shown that Delany-Bazley and Miki models can accurately predict surface impedance of multi-component polyester nonwovens, but Komatsu model has inaccuracy in prediction especially at low-frequency band. The results indicate that Miki model is the most acceptable method to predict the sound absorption coefficient with mean error 8.39% from all the samples.

Perpendicularly-laid nonwovens with varying thickness and areal density were prepared by heat-pressing method to investigate the effect of structural parameters such as thickness and areal density on compressibility. The results also show that the compressional resistance has a strong relation with porosity, the adjusted coefficients of determination is 0.97, indicating that the compressional resistance is directly proportional to the density of perpendicularly-laid nonwovens. The results indicate that the perpendicularly-laid nonwovens with higher initial fibrous layer orientation angle have better compression properties.

An experimental investigation on the thermal properties of perpendicularly-laid nonwovens was carried for establishing relationship between thermal and acoustic properties. It was also observed that sound absorption, the NRC and mean value of sound absorption coefficient ($\bar{\alpha}$), have insignificant correlation with thermal conductivity, while they are strongly correlated with thermal resistance. The adjusted coefficients of determination of NRC with thermal resistance is 0.9835, indicating that NRC is directly proportional to thermal resistance of perpendicularly-laid nonwovens.

This study also investigated the air permeability of perpendicularly-laid nonwovens and their relation to acoustic performance. It was observed that $\bar{\alpha}$ were inversely proportional to air permeability, with adjusted coefficients of determination 0.95. It was concluded that air permeability can be used as a criterion of sound absorption behavior of perpendicularly-laid nonwovens, a lower air permeability suggested a better sound absorption performance for perpendicularly-laid nonwoven fabric.

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8 List of papers published by author

8.1 Journal Publications

[1] **Tao Yang**, Xiaoman Xiong, Rajesh Mishra, Jan Novák, and Jiří Militký. "Acoustic Evaluation of Struto Nonwovens and Their Relationship with Thermal Properties." *Textile Research Journal* 88, no. 4 (February 1, 2018): 426–437 (***Impact factor: 1.540***).

[2] **Tao Yang**, Xiaoman Xiong, Rajesh Mishra, Jan Novák, Jiří Chaloupek, Filip Sanetrnik, and Jiří Militký. "Investigation on Acoustic Behavior and Air Permeability of Struto Nonwovens." *Fibers and Polymers* 17, no. 12 (December 2016): 2078–2084 (***Impact factor: 1.353***).

[3] **Tao Yang**, Xiaoman Xiong, Rajesh Mishra, Jan Novák, and Jiří Militký. "Sound Absorption and Compression Properties of Perpendicularly-laid Nonwovens." *Textile Research Journal*, January 18, 2018, doi: 10.1177/004051751775363(***Impact factor: 1.540***).

[4] **Tao Yang**, Xiaoman Xiong, Mohanapriya Venkataraman, Rajesh Mishra, Jan Novák and Jiří Militký. "Investigation on sound absorption properties of aerogel nonwoven blankets." *The Journal of the Textile Institute,* Accepted (***Impact factor: 1.174***).

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[6] **Tao Yang**, Xiaoman Xiong, Ferina Saati, Kai Yang, Rajesh Mishra, Kirill V Horoshenkov, Rajesh Mishra, Steffen Marburg and Jiří Militký. "Study on sound absorption behavior of multi-component polyester nonwovens: Practical and numerical methods." *Textile Research Journal* (Under review).

[7] Xiaoman Xiong, **Tao Yang**, Rajesh Mishra, Hiroyuki Kanai, Jiri Militky, Thermal and Compression Characteristics of Aerogel-encapsulated Textiles, *Journal of Industrial Textiles*, Vol.47, 1998-2013, 2017 (***Impact factor: 1.283***).

[8] Xiaoman Xiong, **Tao Yang**, Rajesh Mishra, Jiri Militky and Jakub Wiener, Investigation on Laser Engraving based Application of Silica Aerogel into Nonwovens, *Fibers and Polymers*, Vol.18, No. 12, 2469-2475, 2017 (***Impact factor: 1.353***).

[9] Xiaoman Xiong, **Tao Yang**, Rajesh Mishra, Jiri Militky, Transport Properties of Aerogel-based Nanofibrous Nonwoven Fabric, *Fibers and Polymers*, Vol.17, No.10, 1709-1714, 2016 2084 (***Impact factor: 1.353***).

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[11] Xiaoman Xiong, Mohanapriya Venkataraman, Darina Jašíková, **Tao Yang**, Rajesh Mishra and Jiří Militký, Thermal performance of aerogel-encapsulated fibrous materials by convection, under preparation.

8.2 Book Chapters

[1] **Tao Yang**, Xiaoman Xiong, Rajesh Mishra, Jan Novak and Jiří Militký, Comparative Analysis on Acoustic Properties of Different Struto-type Nonwovens, Advances in fibrous material science, ISBN 978-80-87269-48-0, 2016.

[2] **Tao Yang**, Xiaoman Xiong, Rajesh Mishra, Jan Novák, Filip Sanetrník and Jiří Militký, A Review of Acoustic Properties Measurements and Wave Propagation Models of Porous Materials, Recent developments in fibrous material science, ISBN 978-80-87269-45-9, 2015.

[3] Xiaoman Xiong, **Tao Yang**, Rajesh Mishra, Juan Huang and Jiří Militký, A Review on Nanofibrous Membranes and Their Applications, Advances in fibrous material science, ISBN 978-80-87269-48-0, 2016.

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8.3 Conference Publications

[1] **Tao Yang**, Xiaoman Xiong, Rajesh Mishra and Jiri Militky. Relationship Between Sound Absorption Property and Transmission Behavior of Struto Nonwoven, Textile Bioengineering and Informatics Symposium, TBIS-2017, Wuhan, China, 18-20 May, 2017.

[2] **Tao Yang**, Xiaoman Xiong, Rajesh Mishra and Jiri Militky. Acoustic and thermophysiological properties of Struto nonwovens, 44th Textile Research Symposium, IIT Delhi, December 14-16, 2016.

[3] **Tao Yang**, Xiaoman Xiong, R Mishra, V. Arumugam, Mohanapriya Venkataraman and Jiri Militky. Study on Acoustic and Thermal Performance of Struto Nonwovens, 21st Strutex, december 1-2, p. 345-350, ISBN:9788074942693, Liberec, 2016.

[4] **Tao Yang**, Xiaoman Xiong and R. Mishra. 3D orthognal fabric composites from carbon fiber, 8th TBIS-APCC International conference, Zadar, 14-17 June, 2015.

[5] **Tao Yang,** Xiaoman Xiong, R Mishra, Jan Novák and Jiri Militký. Sound absorption behaviour of perpendicular-laid nonwovens, 46th Textile Research Symposium, Teijin Academy Fuji, Japan, September 3-5, 2018.

[6] Xiaoman Xiong, **Tao Yang**, Rajesh Mishra, Jiri Militky, Transport Properties of Nonwovens with Aerogel, CLOTECH 2017, Lodz, Poland, October 11-14, 2017.

[7] Xiaoman Xiong, **Tao Yang**, Rajesh Mishra, Jiri Militky, Laser Engraving based Application of Silica Aerogel into Nonwovens for Thermal Insulation, 45th Textile Research Symposium, KIT Kyoto, September 14-16, 2017.

[8] Xiaoman Xiong, **Tao Yang**, Rajesh Mishra, Jiri Militky, Investigation on Thermal and Compression Performance of Aerogel Incorporated Textiles, Textile Bioengineering and Informatics Symposium, TBIS-2017, Wuhan, China, May 18-20, 2017.

[9] Xiaoman Xiong, **Tao Yang**, Rajesh Mishra, and Jiri Militky, Thermophysiological Performance of Aerogel Embedded Electrospun Nonwoven Layers, 44th Textile Research Symposium, IIT Delhi, December 14-16, 2016.

[10] Xiaoman Xiong, **Tao Yang**, Rajesh Mishra, Effect of weaving friction on yarn hairiness and mechanical properties, 8th TBIS-APCC International conference, Zadar, June 14-17, 2015.

9 Curriculum Vitae

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Department	Technical University of Liberec Faculty of Textile Engineering Department of Material Engineering
Address	Studentská 1402/2, 461 17 Liberec 1 Czech Republic
Mobile	+420-776-589-903
Email	tao.yang@tul.cz
Nationality	Chinese
Date of birth	23/01/1981

AREAS OF RESEARCH

- Acoustic and thermal properties of fibrous materials

CURRENT RESEARCH OBJECTIVES

- Study on influence of structural parameters and nanofiber layer on the acoustic properties of high-loft nonwoven
- Acoustic application of aerogel composed with textile fabrics
- Modelling of acoustic properties of nonwoven

EDUCATION

Technical University of Liberec - Liberec, Czech Republic
Pursuing doctoral studies at Faculty of Textile Material and Engineering
Date: July 2014 until now
Thesis: Study of Acoustic Performance of Textiles

Wuhan Textile University - Wuhan, Hubei, China
Master of Textile Material and Engineering
Date: September 2010 to June 2013
Thesis: A Study on Composite of Carbon-fiber 3D Woven and its Properties

INTERNSHIP

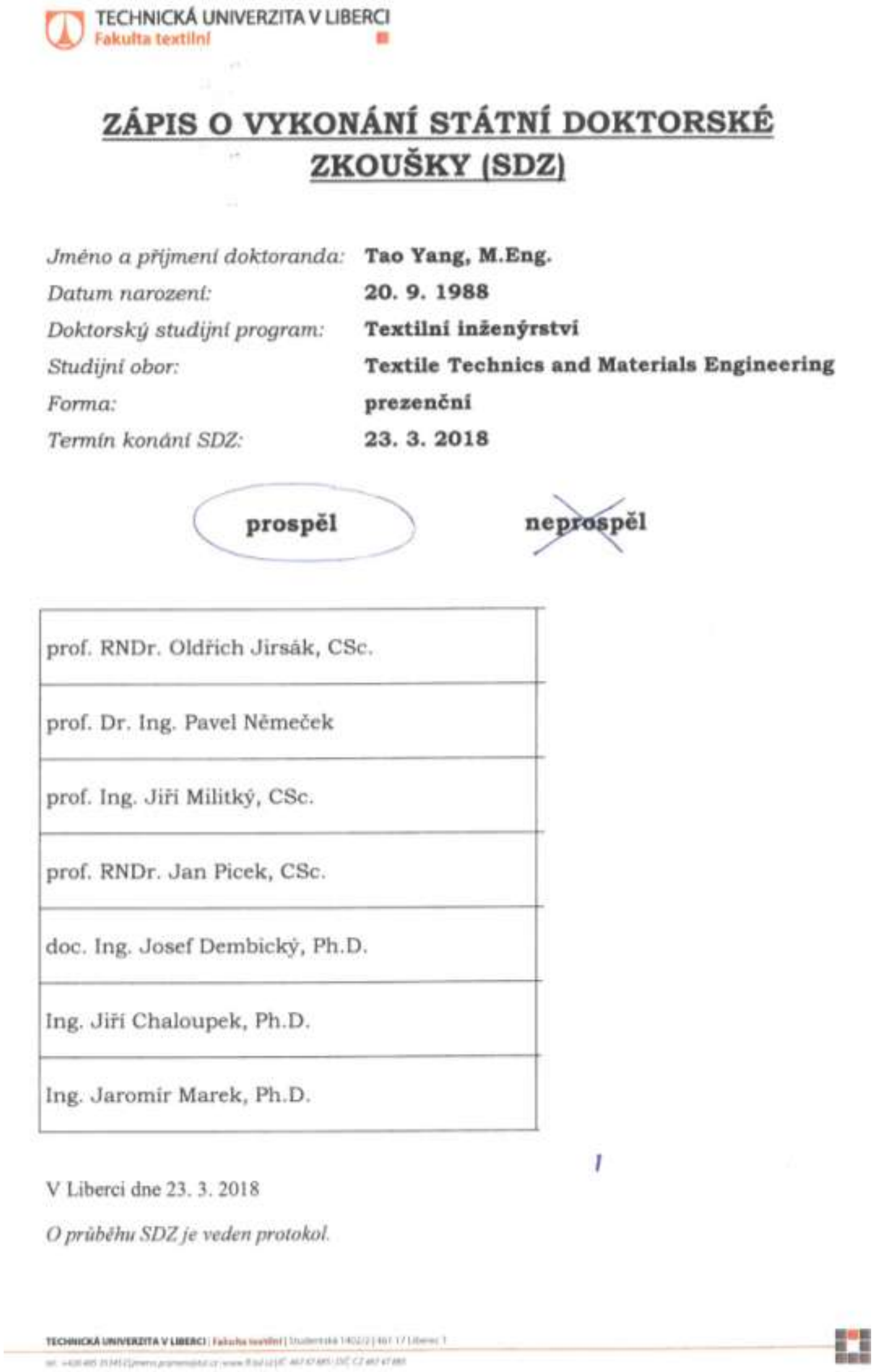
8.2017-10.2017 University of Sheffield Sheffield, UK

- A study of airflow resistivity models for multi-component polyester fiber assembly
- Investigation on the effect of nanofiber layer on the acoustic performance of porous materials

2.2018-3.2018 Le Mans University Le Mans, France

- Determination of acoustic and non-acoustic properties of fibrous material by using 4 microphones impedance tube technique
- Study of 3D anisotropic equivalent fluid model feed by the parameters determined empirically

10 Record of the state doctoral exam



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ZÁPIS O VYKONÁNÍ STÁTNÍ DOKTORSKÉ ZKOUŠKY (SDZ)

Jméno a příjmení doktoranda:	**Tao Yang, M.Eng.**
Datum narození:	**20. 9. 1988**
Doktorský studijní program:	**Textilní inženýrství**
Studijní obor:	**Textile Technics and Materials Engineering**
Forma:	**prezenční**
Termín konání SDZ:	**23. 3. 2018**

[✓ **prospěl**] **~~neprospěl~~**

prof. RNDr. Oldřich Jirsák, CSc.
prof. Dr. Ing. Pavel Němeček
prof. Ing. Jiří Militký, CSc.
prof. RNDr. Jan Picek, CSc.
doc. Ing. Josef Dembický, Ph.D.
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11 Recommendation of the supervisor

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Supervisor's opinion on PhD thesis of Mr. Tao Yang, M.Eng.

Thesis title: **Advanced Fibrous Materials for Acoustic Performance**

Mr. Tao Yang, M.Eng., has worked for his PhD thesis under my supervision since 2014. His research is focused on Advanced Fibrous Materials for Acoustic Performance.

In his work, he has developed perpendicularly-laid nonwoven samples by two different manufacturing techniques: vibration and rotating perpendicular lapper. Heat-pressing method was employed to form samples with varying thickness. This study determines the influence of some structural characteristics and laying techniques on the sound absorption properties of perpendicularly-laid nonwovens. The compression energy and compression load of perpendicularly-laid nonwovens were carried out by using a universal testing machine (TIRATEST 2300). The potential compression mechanism of the nonwoven fabric was identified with support of the compression stress-strain curve, work done and efficiency at different compression stages.

Perpendicularly-laid nonwoven fabrics have special thermal and air permeability behavior compared with traditional cross-laid nonwovens due to their through-plane fiber orientation. Hence this research work also investigates the influence of different structural parameters of perpendicularly-laid nonwoven fabrics, such as areal density, porosity, thickness, on thermal properties and air permeability. The potential relationships between thermal resistivity, air permeability and acoustic properties were also investigated.

His publication activities are in excellent level. Tao Yang has published about 15 papers in international journals with impact factor. Some more are under review and expected to be published soon. He has presented more than 15 papers individually or jointly at international conferences. 5 chapters are published in reputed books. These are strong indicators for his thesis as a comprehensive work of independent research.

The dissertation work is formally correct, parts of the text or images are properly cited and all literary sources are listed in accordance with established rules. Checking of plagiarism on 16. 05. 2019 showed no relevant similarity to other work.

I therefore recommend the thesis for defense.

doc. Rajesh Mishra, PhD
Supervisor

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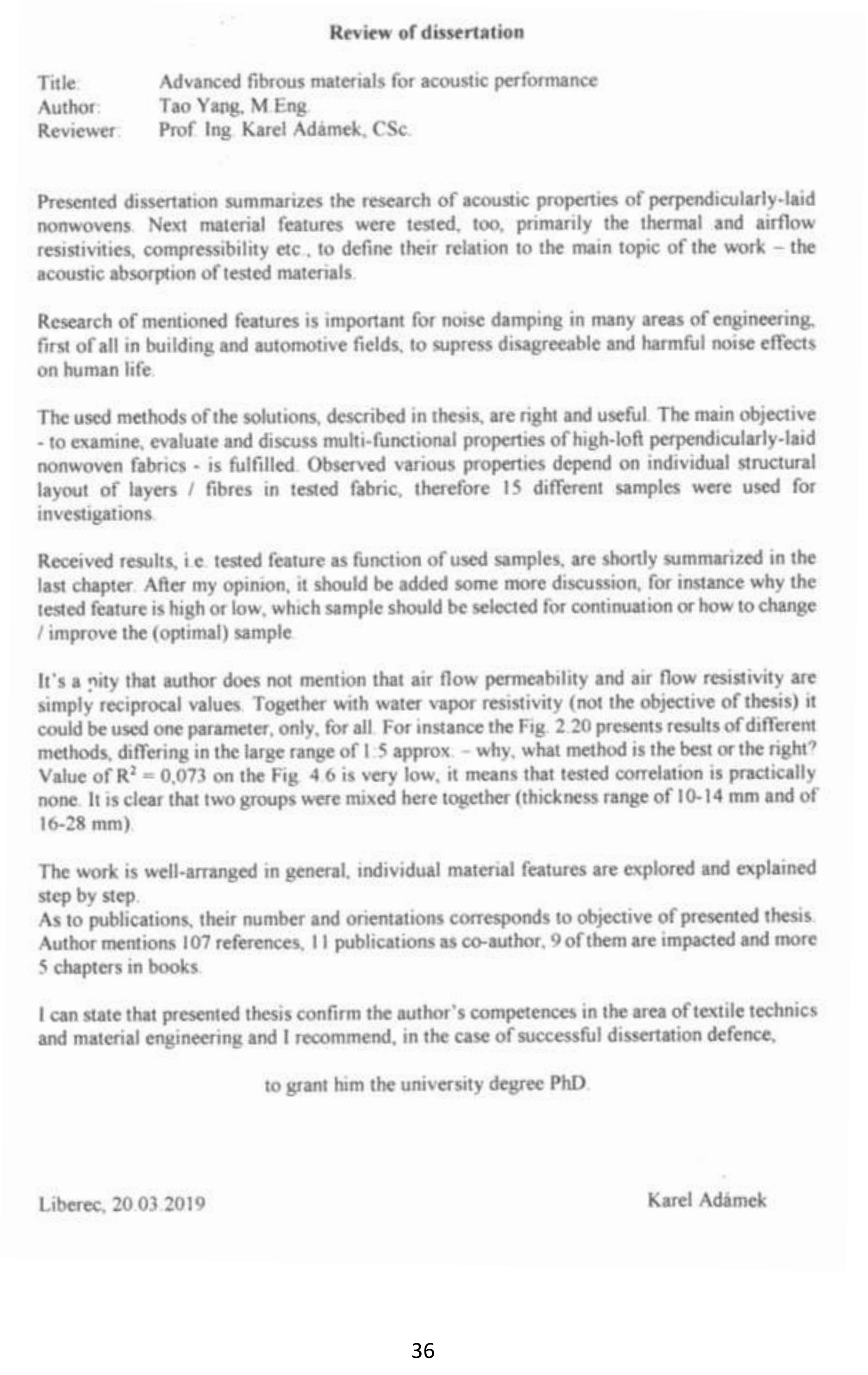
12 Opponent's reviews



Review of dissertation

Title:	Advanced fibrous materials for acoustic performance
Author:	Tao Yang, M.Eng.
Reviewer:	Prof. Ing. Karel Adámek, CSc.

Presented dissertation summarizes the research of acoustic properties of perpendicularly-laid nonwovens. Next material features were tested, too, primarily the thermal and airflow resistivities, compressibility etc., to define their relation to the main topic of the work – the acoustic absorption of tested materials.

Research of mentioned features is important for noise damping in many areas of engineering, first of all in building and automotive fields, to supress disagreeable and harmful noise effects on human life.

The used methods of the solutions, described in thesis, are right and useful. The main objective - to examine, evaluate and discuss multi-functional properties of high-loft perpendicularly-laid nonwoven fabrics - is fulfilled. Observed various properties depend on individual structural layout of layers / fibres in tested fabric, therefore 15 different samples were used for investigations.

Received results, i.e. tested feature as function of used samples, are shortly summarized in the last chapter. After my opinion, it should be added some more discussion, for instance why the tested feature is high or low, which sample should be selected for continuation or how to change / improve the (optimal) sample.

It's a pity that author does not mention that air flow permeability and air flow resistivity are simply reciprocal values. Together with water vapor resistivity (not the objective of thesis) it could be used one parameter, only, for all. For instance the Fig. 2.20 presents results of different methods, differing in the large range of 1:5 approx. – why, what method is the best or the right? Value of $R^2 = 0{,}073$ on the Fig. 4.6 is very low, it means that tested correlation is practically none. It is clear that two groups were mixed here together (thickness range of 10-14 mm and of 16-28 mm).

The work is well-arranged in general, individual material features are explored and explained step by step.
As to publications, their number and orientations corresponds to objective of presented thesis. Author mentions 107 references, 11 publications as co-author, 9 of them are impacted and more 5 chapters in books.

I can state that presented thesis confirm the author's competences in the area of textile technics and material engineering and I recommend, in the case of successful dissertation defence,

to grant him the university degree PhD.

Liberec, 20.03.2019

Karel Adámek

Ph.D. Thesis Review

Advanced Fibrous Materials for Acoustic Performance

Author: **Tao Yang**
Technical university of Liberec
Faculty of textile engineering
Department of Material Engineering

Supervisor: doc. Rajesh Mishra, Ph.D

Author of Review: prof. Dr. Ing. Pavel Němeček
Technical university of Liberec
Faculty of mechanical engineering

The thesis is divided into five chapters with an abstract at the beginning.

Chapter 1: Introduction - in this chapter author describes the main goals of the thesis and all the research objectives are presented and described in detail. Author also briefly describes other chapters of the thesis in this section

Chapter 2: State of the Art in Literature - this chapter provides theoretical background and also explains mechanisms and describes materials used later in the thesis. Author provides us with the definition of sound absorption mechanism, sound absorption materials and also describes in detail parameters of fibrous materials such as fiber size, structural parameters, airflow resistivity, thermal properties, air permeability, etc. Author also reviews previous works written about the same or related topic.

Chapter 3: Experimental part - in this chapter author uses theory described in previous chapter and provides us with results of measurements. At the beginning of this chapter, there is a table with all the materials used later, schematics of measurement environment and photos of devices. Author describes every measurement well.

Chapter 4: Results and Discussion - in fourth and longest chapter author reviews his results and conclusions. Author compares all the results with calculated numerical values and also compares different materials with each other. All the results are well documented and all the parameters of fibrous materials and their sound absorption properties are described correctly.

Chapter 5: Conclusions - in last chapter author summarizes results of the thesis and proposes ways how to use results of this thesis in future work. This chapter also contains references in books, journal publications and conference entries.

Benefits of the thesis

1. Author performed necessary experiments and found connections between observed values and sound absorption. Author used available measurement devices and software. Gained amount of values is big and can be used in further research.
2. Author summed up available models, applied data on them and compared gained values with experiment. He reach the result he critically evaluated.
3. Author used defined materials which can be used in further application.
4. Results of the thesis are supported by current academic research and mathematical procedures are commented and it is possible to verify them. I consider results to be correct and critically evaluated.

Shortcomings of the thesis

1. Author used only results of the measurement in impedance tube and did not consider the relationship between observed models and sound absorption in omnidirectional impact of sound waves.
2. Author used correlation analysis, but did not commented its impact (coefficients of equations y, b). It is then unclear why was this analysis performed so thoroughly. Observed dependencies are just stated.

Final comments

Submitted dissertation work did reach its goals. Author showed abilities of independent research and ability to work with advanced experimental resources and software. I did not find significant shortcomings and

I recommend this Ph.D. thesis to be defended.

Questions

1. Do you consider the results of dependencies to be valid also for sound absorption in omnidirectional impact of sound waves?
2. What statistical model do experimentally researched data of sound absorption have?

In Liberec on May 13, 2019 prof. Dr. Ing. Pavel Němeček