

Evaluation and Comparison of Acoustic Performance and Thermal Conductivity of Spacer Fabrics[★]

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Abstract

The utilization of 3-Dimensional (3D) porous textile materials by the civil and mechanical engineers for improved thermo-acoustic environment has widened the research scope. Unconventional three-dimensional textile material which grabs the attention of the researchers for multi-functional applications is spacer fabrics. Since spacer fabrics have superior thermal and acoustic characteristics compared to conventional woven/knitted structures or nonwovens due to their wonderful 3D porous nature. It has two outer layer connected with the help of monofilament or multifilament spacer yarn which kept the fabric bulkier with low density and highly breathable. Due to porous nature, interconnected pores, bulkier and 3D structure, the spacer fabrics have ability to attenuate more sound energy than the conventional materials. This research paper presents an experimental investigation on the sound absorption behaviour and thermal properties of warp knitted spacer fabrics. The Sound absorption coefficient (SAC) and thermal conductivity (K) were measured using two microphone impedance tube and Alambeta. This study deeply discusses the influence of material parameters and characteristics on acoustic properties of 3D spacer knitted fabrics. The results show that the fabric surface property, porosity, flow resistivity and tortuosity have significant effects on the sound absorption as well as thermal conductivity. With the obtained results, this work derives regression equations and correlation between noise absorption and thermal properties of spacer fabrics.

Keywords: Noise Reduction Coefficient (NRC); 3D Spacer Fabrics; Flow Resistivity; Thermal Conductivity

1 Introduction

The materials and structures using noise reduction or sound insulating materials are to reduced ambient noise have received much attention [1]. Noise is an unwanted level of sound and unfor-

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tunately most of the machines that have been developed for industrial purposes for high speed transportation or to make life more comfortable are accompanied by noise. Noise-absorbing materials absorb unwanted sound by dissipating sound wave energy when it passes through and also by converting some of the energy in to heat. Noise can cause different types of negative effects on humans that are exposed to it inside auditoriums, theatres and even can damage buildings. The effects on humans are hearing loss, change of individual behaviour, reduction of sleep, communication interference and effect on domestic animals and wildlife [2]. A healthy young person can hear sound in the frequency range of about 20 Hz to 20000 Hz, but speech is composed of sound mostly in the range of 200 Hz to 6000 Hz. The frequency range where the human ear is most sensitive is 200 Hz to 2000 Hz. There are several methods to decrease noise and one of them is the use of sound absorption materials. Porous material is a typical passive medium widely used for sound absorption. Sound absorbability of this kind of material also depends on the sound wave frequency [3, 4]. The acoustic performance of sound absorbing poro-elastic materials is governed by its five intrinsic physical parameters like flow resistivity, porosity, tortuosity, viscous and thermal characteristic lengths [5]. The most important parameter which determines sound-absorptive and sound-transmitting properties of acoustic materials is the flow resistivity.

The absorption of sound results from the dissipation of sound energy, owing to the viscous friction and heat exchange when sound waves propagate and reflect through the flexible porous structure [6]. Many authors have explained this dissipation mechanism in the past [2, 6]. Noise-absorbing materials absorb unwanted sound by dissipating sound wave energy when it passes through and also by converting some of the energy in to heat, making them useful for control of noise. Porous material is a typical passive medium widely used for sound absorption. In general a porous material with rigid backing absorbs more at middle and high frequencies than at low frequencies of sounds [7]. Porous material is a typical passive medium widely used for sound absorption. Sound absorbability of this kind of material depends on the sound wave frequency. Currently, successful sound absorption materials commercially available for acoustic treatment consist of rigid porous medium, micro perforated panels, nonwovens and composites. Various studies and research on textile fabrics, nonwoven mats etc. have been conducted in order to analyze their noise absorption performance [8, 9]. These studies suggested some drawbacks in existing materials like poor performances, bad structural stability, difficult to produce with textured surface for aesthetics etc. Hence in order to overcome all these drawbacks, 3-dimensional spacer fabrics grab the attention of researchers in this decade.

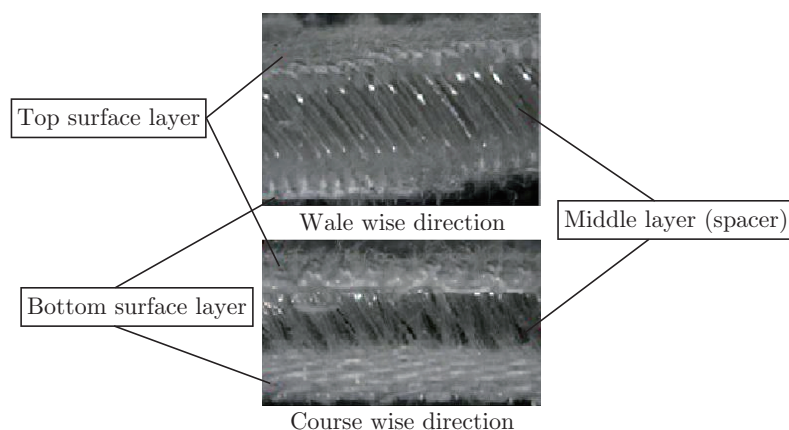


Fig. 1: Structure of spacer fabrics [13]

The major application areas of spacer fabrics are acoustics and automotive, aerospace, civil engineering, medical field, geotextiles, protective textiles, sportswear and composites [10, 11]. Spacer fabrics are a class of material with unique properties and applications. They are lightweight and designed to undergo very large deformations. They are typically used in packing and to absorb energy. As shown in Fig. 1, Owing to the superior structural properties of spacer fabrics such as 3D fibre disposition, inter connected pores, low density, possibility to use different materials and single step production system, enable them in acoustic applications such as automobile upholstery, auditoriums, theatres etc. Researchers investigated sound absorption of thick knitted spacer fabrics knitted from covered elastomeric yarn in their study. The results of their study showed better noise absorption when there is a thicker air gap between the front and fabric layers of the spacer fabric and/or a thicker face layer. Since good thermal and acoustic performance of materials are necessary when the materials are used as inner lining of automobiles, on the walls inside buildings or any other indoor environment [12]. Therefore, the current study reports the thermo-acoustic performance of warp knitted spacer fabrics.

2 Materials and Methods

Six different spacer fabrics made up of polyester filament yarn were knitted using Raschel warp knitting machine with gauge of E22 and 6 guide bars. The samples classification is clearly presented in Table 1. The structure and knit pattern of lock knit warp knit structures are given in Fig. 2. Structural properties including the yarn linear density and fabric weights per unit area were determined according to ASTM D1059 standard using electronic weighing scales. The thickness of the fabrics was measured according to ASTM D1777-96 standard with the SDL digital thickness gauge at a pressure of 200 Pa. The stitch density was calculated from Wales per centimetre (WPC) and course per centimetre (CPC) with the help of Digital Optical Microscope, DN100, Nikon Inc. as per standard ASTM D 3887. The density (D) of the fabric was calculated using the relationship in Eq. (1) [13, 14],

$$D = \frac{W}{t} \text{ kg/m}^3 \quad (1)$$

Table 1: Description of warp knitted spacer fabrics

| S.No. | Structure | Fibre Composition (%) | Face Layer (dtex) | Middle Layer (Spacer) (dtex) | Back Layer (dtex) | Spacer Yarn Dia (mm) |
|-------|-----------|-----------------------|-------------------|------------------------------|-------------------|----------------------|
| WAS 1 | Lock knit | 100% Polyester | 83f36 | 33f1 | 83f36 | 0.055 |
| WAS 2 | Lock knit | 100% Polyester | 83f36 | 33f1 | 83f36 | 0.055 |
| WAS 3 | Lock knit | 100% Polyester | 83f36 | 33f1 | 83f36 | 0.055 |
| WAS 4 | Lock knit | 100% Polyester | 83f36 | 108f1 | 83f36 | 0.1 |
| WAS 5 | Lock knit | 100% Polyester | 83f36 | 108f1 | 83f36 | 0.1 |
| WAS 6 | Lock knit | 100% Polyester | 83f36 | 108f1 | 83f36 | 0.1 |

where, W is areal density (weight per unit area) and t is thickness. Porosity, H , was calculated with the Eq. (2), using standard test methods for apparent porosity ASTM C 830-00,

$$H = 1 - \frac{\rho_a}{\rho_b} \quad (2)$$

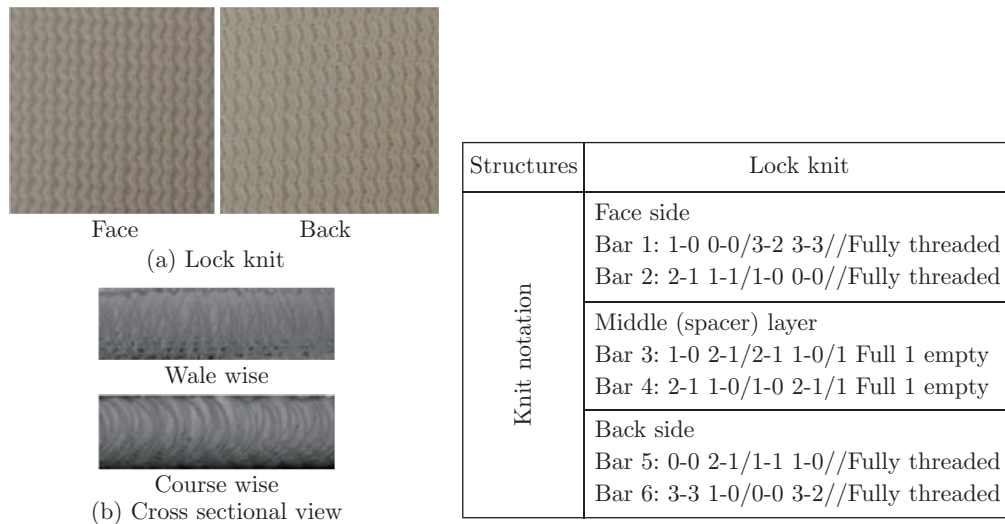


Fig. 2: Structure and knit pattern of warp knit spacer fabrics

where, ρ_b is bulk density of spacer fabrics, ρ_a is weighted average absolute density of polyester (1.36 g/cm^3) fibres in the spacer fabric, expressed in kg/m^3 . The fabric characteristics such as areal density, stitch density, porosity density and thickness, are presented in Table 2. All the experiments were carried out under standard ambient condition and as per standard.

Table 2: Characteristics of spacer fabrics

| Warp Spacer Samples | Stitch Density (Stitches/cm ²) | | | | GSM ($\text{g} \cdot \text{m}^{-2}$) | | | | Thickness (mm) | | | | Density ($\text{Kg} \cdot \text{m}^{-3}$) | Porosity (%) |
|---------------------|--|-----|--------|--------|--|-----|--------|--------|----------------|------|------|------|---|--------------|
| | Mean | ME | LL | UL | Mean | ME | LL | UL | Mean | ME | LL | UL | | |
| WAS 1 | 120.4 | 1.1 | 119.30 | 121.50 | 262.3 | 0.7 | 261.6 | 263.1 | 1.50 | 0.03 | 1.47 | 1.53 | 174.89 | 87.33 |
| WAS 2 | 121 | 1.4 | 119.60 | 122.40 | 354.3 | 0.8 | 353.6 | 355.1 | 2.50 | 0.04 | 2.46 | 2.54 | 141.73 | 89.73 |
| WAS 3 | 120.3 | 1.3 | 119.00 | 121.60 | 446.0 | 3.1 | 442.9 | 449.1 | 3.50 | 0.03 | 3.47 | 3.53 | 127.42 | 90.77 |
| WAS 4 | 119 | 1.2 | 117.80 | 120.20 | 573.1 | 0.7 | 572.4 | 573.8 | 1.50 | 0.02 | 1.48 | 1.52 | 382.06 | 72.31 |
| WAS 5 | 120 | 1.1 | 118.90 | 121.10 | 871.9 | 0.6 | 871.3 | 872.5 | 2.50 | 0.01 | 2.49 | 2.51 | 348.77 | 74.73 |
| WAS 6 | 120.5 | 0.9 | 119.60 | 121.40 | 1174.1 | 0.7 | 1173.4 | 1174.8 | 3.50 | 0.01 | 3.49 | 3.51 | 335.47 | 75.69 |

*ME — Margin of Errors, LL— Lower Limit, UL — Upper Limit

2.1 Air Flow Resistance

Air flow resistance of spacer fabric was calculated from air permeability value obtained from Textest FX-3300 air permeability tester from TexTest, Switzerland. The air permeability is described as the rate of air flow passing perpendicularly through a known area, under a prescribed air pressure differential between the two surfaces of a material (200 Pa). Tests were performed according to standard ISO 9237 for five specimens of each sample. The textest instrument gave the rate of flow of air in cubic meter per square metre of sample area per second. These units have

been converted in to air flow resistivity (R) with the support of pressure difference and thickness of the sample as shown in Equation (3) [6],

$$\text{Air Flow Resistivity, } R = \frac{\nabla P}{v * d} \text{Pa} \cdot \text{m}^{-2} \cdot \text{s} \quad (3)$$

where R —air flow resistivity, ∇P —Pressure difference in Pascal (Pa), v —linear air flow velocity in m/s, d —thickness in metre.

2.2 Determination of Tortuosity

The tortuosity is a fundamental parameter which describes complexity of the path of sound wave propagating within a porous material. The tortuosity is defined from the ratio of the path in the pores between two points on the propagation axis in the porous medium separated by a great distance and the length of the straight line joining the points.

The tortuosity is mainly used to describe the diffusion in porous media such as foams, non woven's, thick fabrics etc, also for soil and snow. The measurements are performed by positioning the samples between two ultrasonic transducers, one is emitter and the other is receiver as shown in Fig. 2. The method is based on the increase of the time of flight of an ultrasonic pulse when the sample is introduced between the two transducers. The emitter provides ultrasonic pulse with high frequency of 40 kHz. At high frequencies, i.e. when the viscous skin depth is very small compared to the pore size, the speed of sound is almost same as in air. The experimental set up is shown in Fig. 3. As shown, the computer generates the signal and simultaneously records the received signal via power amplifier. The experiment is performed with the sample positioned between two transducers and then compared with reference signal (without sample) to extract the relative time delay and amplitude attenuation (Fig. 3). From the time delay (τ) and attenuation ratio amplitude (T) with/without sample of signal time, it is possible to calculate tortuosity using the Eq. (4) given below [6].

$$\text{Tortuosity, } K_S = \left[\left(\frac{|\ln(T)| c_o}{d\omega} \right) - \sqrt{\left(\frac{|\ln(T)| c_o}{d\omega} \right)^2 + \left(1 + \frac{c_0\tau}{d} \right)} \right]^2 \quad (4)$$

where, K_S —Tortuosity (no unit), T —Attenuation ratio amplitude ($|\ln(T)| = a*d$), a —Attenuation per unit length, d —thickness of Material (mm), ω —Ultrasound Frequency (40 kHz), C_0 —Speed of sound in free air (343 m/s), τ —Time delay in (μs).

2.3 Thermal Properties

In this study the thermal conductivity of spacer fabric was measured using Alambeta. The principle and measuring technique of this test method is given below. The thermal property was studied by Alambeta instrument. The measurements of thermal insulation parameters were performed on spacer fabrics with the use of the ALAMBETA device constructed by Hes (Czech Republic). Alambeta measuring device is the fast measuring of transient and steady state thermo-physical properties (thermal insulation and thermal contact properties). The instrument measures the sample thickness also. The Alambeta simulates the dry human skin and its principle depends

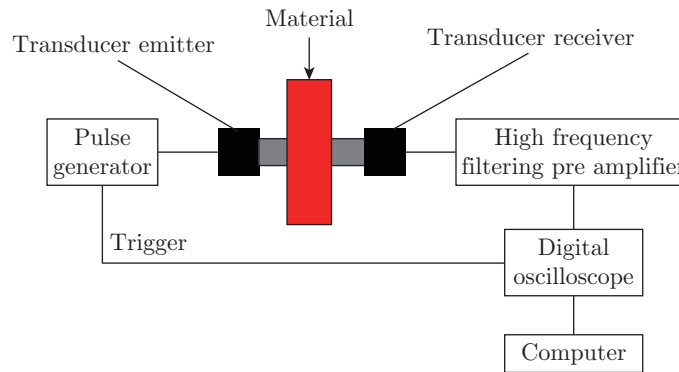


Fig. 3: Experimental set up to measure tortuosity using ultrasonic method

on mathematical processing of time course of heat flow passing through the tested fabric due to different temperatures of bottom measuring plate (22 °C) and measuring head (32 °C). When the specimen is inserted, the measuring head drops down, touches the fabric and the heat flow levels are processed in the computer and thermal properties of the measured specimen are evaluated. The measurement lasts for several minutes only. Six parameters were determined: thermal conductivity λ , thermal diffusion a , thermal absorption b , thermal resistance r , the ratio of maximal to stationary heat flow density v , and stationary heat flow density q_s at the contact point.

2.4 Sound Absorption Properties

In this research, the impedance tube method was used to determine the normal incident sound SAC (α). A minimum of five specimens for each sample were tested according to ASTM E 1050-07 using impedance tube (Type 4206) from Bruel and Kjaer, Denmark. Standard test method for impedance and absorption of acoustic materials using a tube with two microphones and a digital frequency analysis system was used (Fig. 4). In this study, the impedance tube method was used, which is faster and generally reproducible and, in particular it requires relatively small circular samples, both 29 and 100 mm in diameter according to the frequency range (former measures 500 Hz to 6.4 kHz and later 50 Hz to 500 Hz). The working principle of this method is, the broad band sound waves produced by the loud speaker formed in the tube generates stationary wave pattern. This stationary wave pattern composed of incident and reflected sound waves that strike straight to the material which is placed in opposite side of the tube. The incident and the reflected or not absorbed components of the wave pattern are analyzed with simultaneous pressure measurements at two locations in the tube. A digital frequency analysis system determines the SAC as a function of sound frequency. Thus the method avoids the need to fabricate large test sample with lateral dimensions several times the acoustic wavelength [15].

2.5 Calculation of NRC

The NRC is a measure of how much sound is absorbed by a particular material, and is derived from the measured SAC at different frequencies (Hertz). The most common single number value of sound absorption in Europe is the so-called weighted SAC, whereas in the English-speaking world it is the NRC or the Sound Absorption Average (SAA). The NRC is determined by calculating the mean value from four one-third-octave values of the SAC (250 Hz, 500 Hz, 1000 Hz and 2000

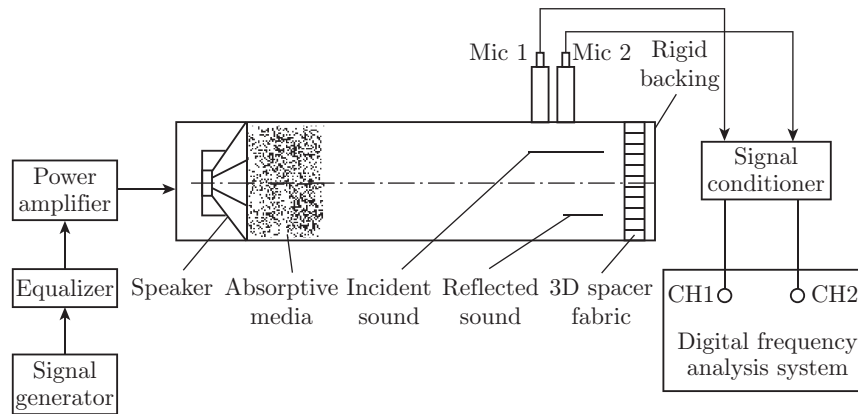


Fig. 4: Impedance tube method (ASTM E 1050-08)

Hz). The NRC was determined using the following formula Eq. (5).

$$NRC = \frac{\alpha_{250 \text{ Hz}} + \alpha_{500 \text{ Hz}} + \alpha_{1000 \text{ Hz}} + \alpha_{2000 \text{ Hz}}}{4} \quad (5)$$

Advance statistical evaluation and two-way analysis of variance was used to analyze the significance of various factors on required properties of warp knitted spacer fabrics. Also, differences in means between various groups were examined for statistical significance using two ANOVA followed by pair comparison using Scheffe's method.

3 Results and Discussions

3.1 Effect of Structural Characteristics on Air Flow Resistivity

The flow resistivity of material is majorly decides by the characteristics such as density, massivity or porosity and tortuosity. One of the most important qualities that influence the sound absorption characteristics of a spacer fabric is the specific flow resistance per unit thickness.

In this section effect of these three characteristics on air flow resistivity of warp knitted spacer fabrics are clearly discussed and presented in Fig. 5. The results show that fabric density has a significant effect on the air flow resistivity values of the spacer fabric, as air flow resistivity tended to increase as density increased, irrespective of yarn linear density and stitch density. As shown in Fig. 3(b), the denser fabrics offer more resistant towards air to pass from one surface to other. Also it was observed from the Fig. 5(a), porous with lower massivity of fabrics offers more permeable to air. Lock knit fabrics (WAS 1 – WAS 6) have tighter surface structure because it inter-loops the filament very close to each other, So, it is resistant to air flow. It was also noticed that the spacer fabrics with finer spacer yarn offer lower resistance to air due to lower density. As compared to the structural parameters of samples, no differences are observed in tortuosity for the samples with almost same stitch density and massivity. So, tortuosity is highly dependent on the thickness, massivity and inner geometry for the spacer fabrics. A small variation in thickness causes a huge impact on tortuosity of air channel in the material. The tortuosity increases with increase in massivity of spacer textile materials (Fig. 5(c)). The torturous (high tortuosity) fabrics results high air flow resistivity because it is obvious that, when the material has more tortuous path, it resists the fluid to flow freely.

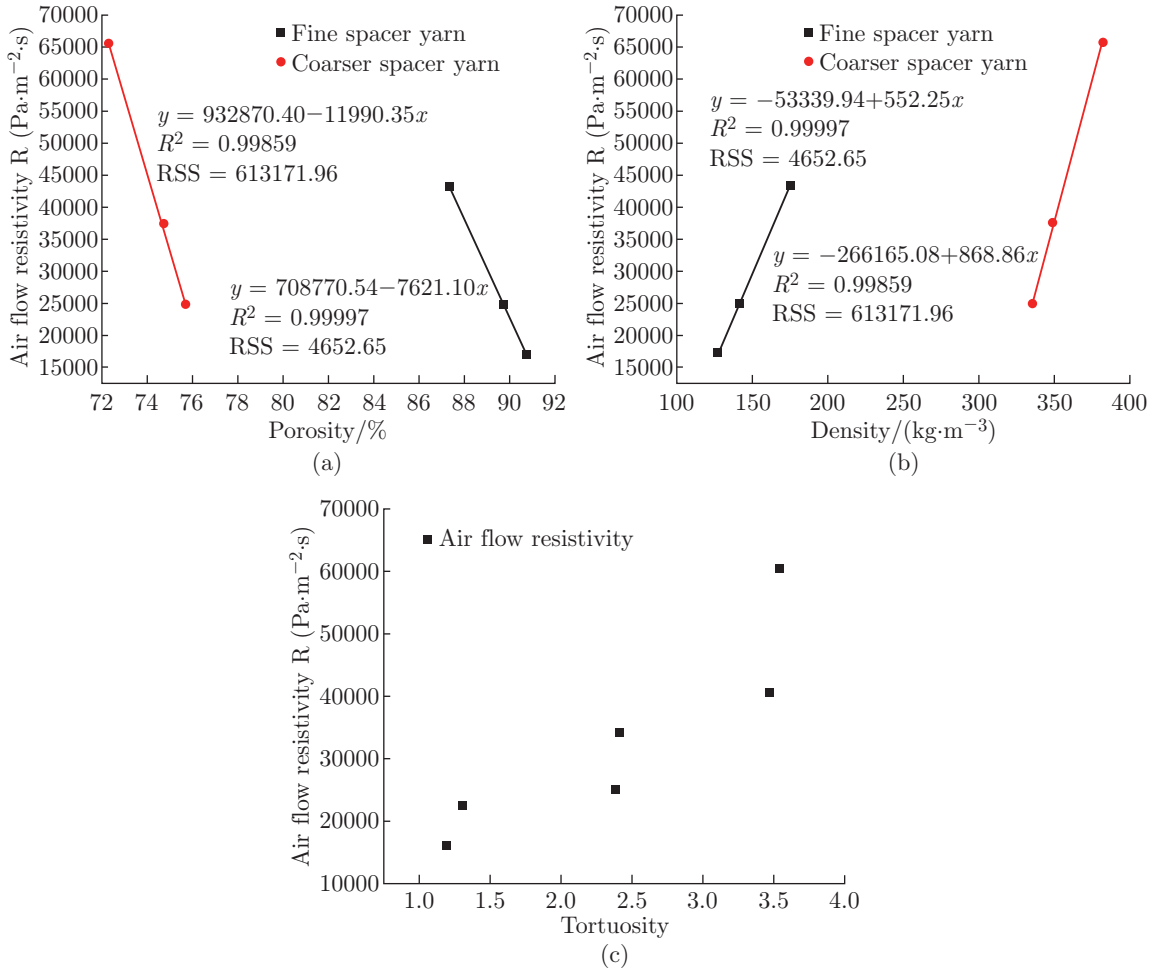


Fig. 5: Effect of structural characteristics on air flow resistivity

3.2 Influence of Fabric Characteristics on Acoustic Performance

As shown in Fig. 6(a) & (b), porosity increases from 75 to 90% for lock knit structure spacer fabrics, warp knit spacer fabrics, the changes on sound absorption is insignificant for low frequency range (50 Hz to 2000 Hz). In middle frequency range, 2000–4500 Hz, the SAC increases drastically when the porosity decreases because of increases in air-flow resistivity. For frequency range above 4500 Hz (high frequency), the significant differences in sound absorption value between the samples can be observed clearly from the Fig. 6, it might be due to the variation in flow resistivity and the thickness. The results obtained show that the thin spacer fabric with high density has higher air flow resistance. In a certain range of the thickness of the materials, the larger density means the denser structure.

The resistance of air particle through the material was increased, and the SAC was decreased. Therefore, thickness of a fabric is often considered to be the important factor that governs the sound absorption behavior of the spacer fabrics. The increase in torturous path of middle (spacer) layer has ability to entrap more air therefore cause higher flow resistance with more sound absorption. The spacer fabrics (WAS 4–WAS 6) are relative shows higher density and lower porosity; allows sound waves to attenuate easily. It was noticed from the Fig. 6(a), the sound absorption capacity of spacer fabrics depends not only air flow resistivity, and it depends surface structure

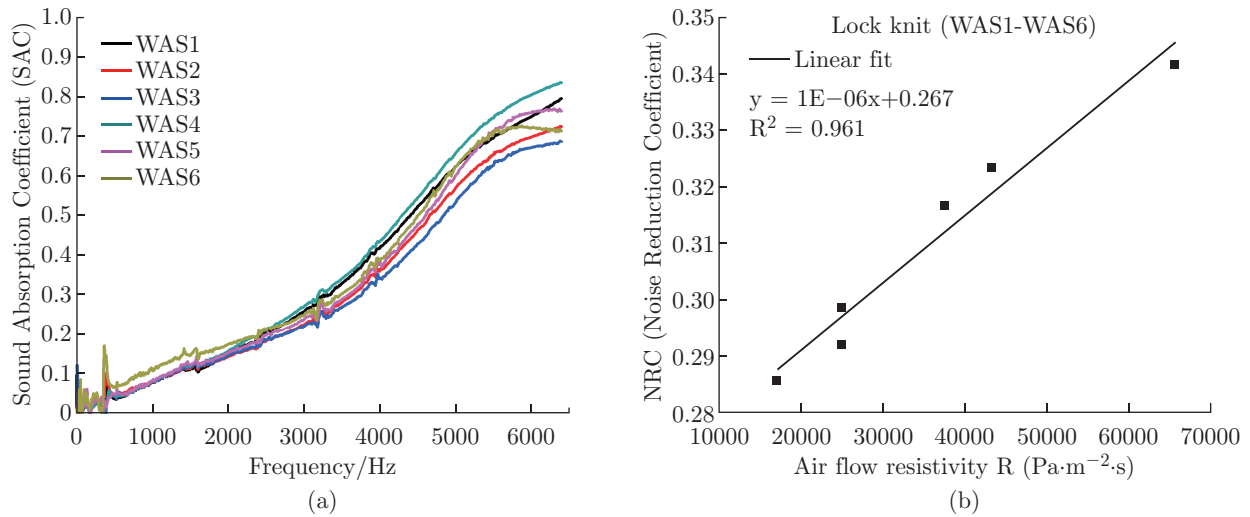


Fig. 6: Influence of fabric characteristics on acoustic performance

structural pores, thickness and density. When the sound wave has to enter the porous material, there should have enough pores on the surface of the material for the sound to pass through and get dampened. This is mainly because of surface roughness (component of surface texture of fabrics) and stitch density (product of Courses and Wales per unit length and is measured in units of loops per square centimetre) of the spacer fabrics which causes sound waves to reflect more on the surface itself. Fig. 6(b) indicates that the NRC of the spacer fabrics increases with the increase in airflow resistivity. Moreover, an increase in airflow resistivity gives rise to a reduction in porosity; thus, the sound absorbency of the fabric increases with the reduction in its porosity. The effect of airflow resistivity has a greater effect on the sound absorbency of the warp knit spacer fabric than its thickness. Moreover, as shown in Fig. 6(b), the airflow resistivity is more or less inversely proportional to the porosity or directly proportional to massivity of the fabric; the effect of massivity thus has a greater effect on its sound absorbency. Further, this would result in the sound absorbency of these fabrics increasing with density.

3.3 Influence of Fabric Characteristics on Thermal Performance

Thermal conductivity and resistance are immensely influenced by the fabric structure and thickness. Increase in fabric thickness will result in increase in thermal insulation, as there will be a decrease in heat losses for the space insulated by the textile. To study the thermal performance of the above samples, characterization and analysis of thermal properties such as thermal conductivity is discussed in this section. The major factors influencing the thermal behavior of fabrics are density, porosity and air permeability. As shown in Fig. 7(a) & (b), the thermal conductivity of spacer fabrics significantly increased with increase in density and decrease in air permeability. Because, the open surface pores in hexagonal fabrics result in higher air permeability make thermally resistant materials comparatively. It is also proved that spacer fabrics with low porosity result in high thermal conductivity, due to fabrics act as a barrier for air permeability.

Overall results give in the way that comparatively higher fabric thickness of a spacer fabric entraps more air within the middle layer and therefore cause higher thermal resistance with lower thermal conductivity. The amount of air entrapped in denser fabrics (WAS 4–WAS 6) is high

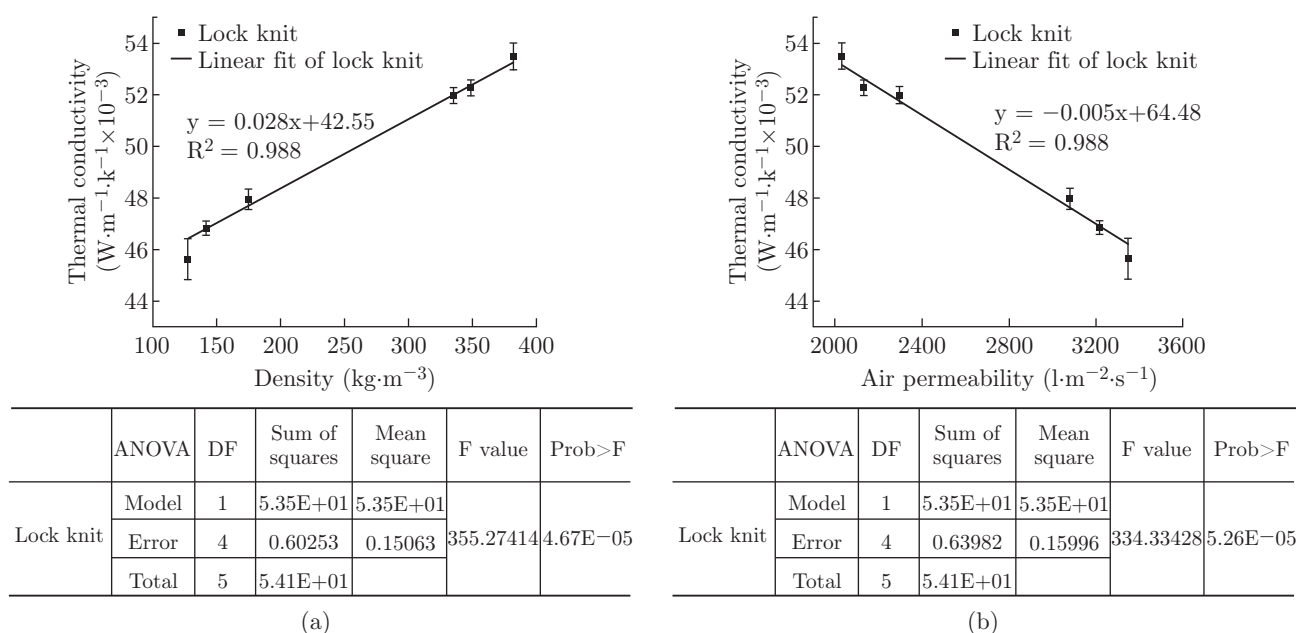


Fig. 7: Influence of fabric characteristics on thermal performance

and it allows conduction of heat causing higher thermal conductivity. Fig. 7 also presents the regression model for thermal conductivity with the effect of density and air permeability. The thermal conductivity of warp knitted spacer fabric has positive linear correlation with density and negative correlation with porosity and air permeability with the coefficient of determinant of more than 0.9.

3.4 Estimation of Correlation between NRC and Thermal Conductivity

The three dimensional structure of a spacer fabric having higher thickness and lower mass leads to higher amount of air trapped in the fabric. If the fabric is in contact with air from one side, the trapped air will circulate between the upper and bottom layers because of the high air permeability in these kinds of fabrics. This feature is responsible to transfer the moisture and heat of skin surface through the circulating air. So, 3D spacer structure will be greatly thermally isolated. In this work the thermal conductivity of spacer fabrics were also measured and compared with acoustic characteristics. The correlation between Noise Reduction Coefficient (NRC) and Thermal Conductivity (k) has been explored using regression least square method and the final fit and equation are shown in Fig. 8 with correlation coefficient. The positive linear correlation trend was found between these two parameters with correlation coefficient of 0.514 as shown in Fig. 8. This equation helps to predict these two parameters for both the group of samples. In Fig. 8, it clearly shows that the NRC and k are directly proportional to each other. The fitting of model is verified with F statistics and probability value. These regression equations are useful to find out the thermal conductivity value (k) and Noise Reduction Coefficient (NRC) value for spacer fabrics design purpose if one variable is known at room temperature.

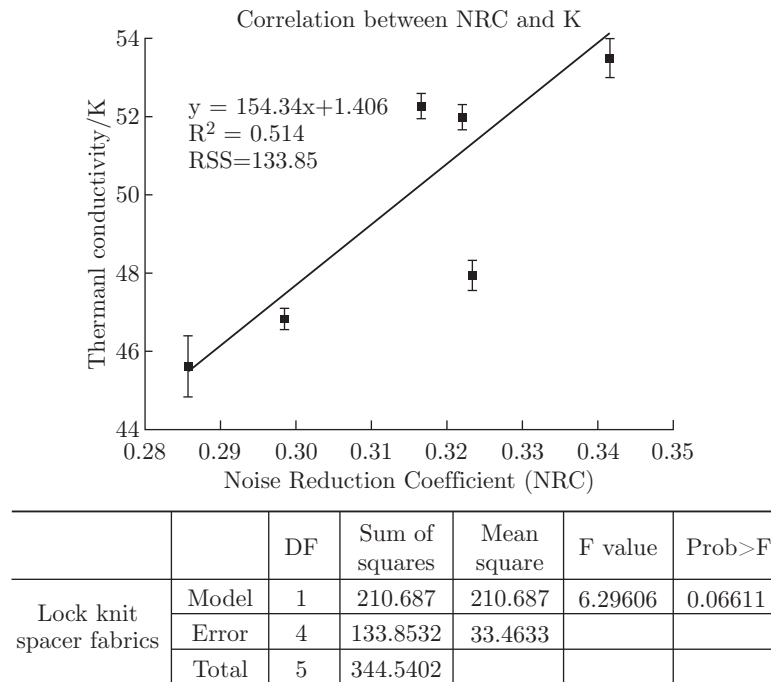


Fig. 8: Correlation between NRC and thermal conductivity

4 Conclusion

In this study, thermal behavior and acoustic performance of warp knitted spacer fabrics were studied and analyzed with the effect of fabric characteristics. Also an attempt has been made to find the correlation between thermal and acoustic properties of spacer fabrics.

(1) The sound absorption capacity of spacer fabrics depends not only on air flow resistivity, but on surface structure, structure of pores, thickness and density.

(2) The reduction in porosity gives rise to airflow resistivity; thus, the sound absorbency of the spacer fabric increases with the reduction in its porosity. The airflow resistivity has a greater effect on the sound absorbency of the warp knit spacer fabrics than its thickness. The airflow resistivity is more or less inversely proportional to the porosity or directly proportional to massivity of the fabric, which has a greater influence on its sound absorbency.

(3) Also the results confirmed that the thickness and surface structures have significant impact on the spacer fabric thermal comfort properties. It is also found the linear regression correlation between the fabric properties.

(4) Instrumental and acceptable positive correlation between thermal conductivity and Noise reduction coefficient were found. It seems that the Thermal conductivity increases with increase in NRC.

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