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A Performance Study on Indirect Acoustic Flow Resistivity Measurement Methods

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Abstract

Various empirical models have emphasized the dependence of sound absorption coefficient on static airflow resistivity, and thus its measurement becomes essential. In this paper, the two-cavity and two-thickness indirect acoustic methods are implemented based on a standard impedance tube for evaluating the static flow resistivity of foam. A comparison is made between the resistivity results obtained by the two-cavity and two-thickness method, and later validated with results of an alternating air-flow test setup which is developed as per the ISO 9053 guidelines. Further, the empirical relations are utilized to estimate the absorption coefficient from measured values of flow resistivity and are compared with measured absorption coefficient in an impedance tube. The results discussed in this study presents the feasibility and suitability of the indirect acoustic methods for evaluating the flow resistivity.

Keywords: Static flow resistivity, Two-cavity, Two-thickness method, Impedance Tube, Absorption Coefficient.

Исследование эффективности косвенных методов измерения удельного сопротивления продуванию для акустических материалов

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Аннотация

Различные эмпирические модели подчеркивают зависимость коэффициента звукопоглощения от статического удельного сопротивления продуванию воздушным потоком, поэтому его измерение становится необходимым. В настоящей работе на основе стандартной импедансной трубе для оценки

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статического удельного сопротивления продуванию для пены реализованы косвенные акустические методы двух полостей и двух слоев. Проведено сравнение результатов измерения удельного сопротивления, полученных методом двух полостей и двух слоев, а затем подтвержденных результатами работы испытательной установки переменного воздушного потока, разработанной в соответствии с нормами ISO 9053. Далее эмпирические соотношения используются для оценки коэффициента поглощения по измеренным значениям удельного сопротивления продуванию и сравниваются с измеренным коэффициентом поглощения в импедансной трубе. Результаты, рассмотренные в настоящем исследовании, показывают целесообразность и пригодность косвенных акустических методов для оценки удельного сопротивления продуванию.

Ключевые слова: *статическое сопротивление продуванию, двухполостной метод, метод двух слоев, импедансная труба, коэффициент поглощения.*

Introduction

The empirical models [1, 2, 3, 4] have been extensively used for estimating the sound absorption coefficient of a homogenous sound absorbing material. These empirical relations require the knowledge of the material's static flow resistivity as a prerequisite which could be readily determined by using various standards or methods. Delany and Bazley [2] recommended the use of simple power law functions to represent the normalized characteristic impedance and propagation constant as a function of the frequency parameter (ratio of frequency to flow resistivity) for fibrous absorbent materials. It was observed that fibre size and bulk density are the two important parameters influencing flow resistivity of fibrous materials. The power law functions could be appropriately used for values of frequency parameter ranging from 0.01 to 1 m^3/kg. The empirical relations recommended by Delany and Bazley could not be confidently used to determine the intrinsic properties for small values of the frequency parameter [1]. Hence, Bies and Hansen [1] further extended the Delany and Bazley empirical relationships to approach the correct limits for small, medium and large values of the frequency parameter. Dunn and Davern [3] followed the Delany and Bazley approach and proposed new regression constants for open-pore polyurethane foams. Thus, depending on the material and frequency considered for the study, a suitable empirical equation could be utilized to estimate the sound absorption coefficient from the known value of static flow resistivity. So, one of the required acoustic material properties is static flow resistivity for estimating sound absorption coefficient using empirical equations. The methods available for measuring the flow resistivity can be categorized as a direct or steady airflow method [5, 6], the alternating airflow method [6, 7], the comparative method [8] and the acoustic method [9, 10, 11, 12, 13].

The direct airflow method requires measurement of two parameters, i.e., the pressure drop across the test specimen and the volume velocity of steady airflow through the test specimen. On the other hand, the alternating airflow method requires only the measurement of pressure drop across the test specimen for a known volume velocity. In case of the ISO 9053 alternating air flow method, the pressure drop is measured at a low frequency of 2 Hz. Dragonetti et al.[7] proposed an alternating method in which the flow resistivity is estimated by using imaginary part of transfer function between two microphones kept in two cavities coupled by a speaker. This method eliminates the need for special instrumentation and calibration as required in case of ASTM C522 and ISO 9053 standards. Thus, the pressure measurements can be performed at frequencies greater than 2 Hz. Stinson and Daigle [8] developed the comparative method based on an electronic system involving two resistive elements placed in series for the measurement of flow resistance. The two elements consist of one with calibrated resistance and the other with unknown resistance. Since, the volumetric flow of air across the elements is constant, the ratio of the pressure drops across each element is the same as the ratio of the values of flow resistance.

The acoustic methods for flow resistance measurement is normally carried out in impedance tubes which can be broadly classified as indirect and inverse methods. The inverse method [9] relies on a sound absorption coefficient, while the indirect method [10, 11, 12, 13] requires evaluation of two intrinsic acoustic properties such as effective density and effective bulk modulus of the material. The indirect acoustic methods can further be classified as two-microphone and three-microphone methods. Ingard and Dear [11] proposed that at low frequencies the ratio of the sound pressures on both sides of the specimen measured in tube-like structure can be used to estimate normalized static flow resistance of acoustic material. Woodcock and Hodgson [13] adopted the two-cavity [14] and two-thickness [15] methods for evaluating the characteristic impedance and propagation constant of fibrous materials and then utilized the Delany and Bazley inverse equations for calculating the effective flow resistivity. Tao et al. [12] proposed an acoustic method based on the impedance transfer function for determination of the static airflow resistivity using a standard impedance tube used in ISO 10534.2 [16]. Doutras et al. proposed three-microphone impedance tube method to evaluate non-acoustic properties like flow resistivity, tortuosity, viscous and thermal characteristic lengths by measuring material's effective density and bulk modulus [10].

The main aim of this research is to discuss the existing flow resistivity measurement methods and to find the feasibility of acoustic methods in measuring static flow resistivity. In this paper, the two-cavity method with arbitrary air-gap and the two-thickness method are implemented for measuring the static flow resistivity of foam samples. In addition, a test setup has been developed as per the ISO 9053 alternating airflow method guidelines for validation of the obtained static flow resistivity values. The performance of the implemented methods is assessed based on the absorption coefficient estimated from their respective static flow resistivity. The results and discussion presented in this study will help in the selection of a suitable method for measuring the static flow resistivity.

1. Methodology

The material's flow resistivity can be basically categorized as dynamic and static. The dynamic flow resistivity varies with frequency. However, it tends to remain constant at low frequencies and hence is termed as static flow resistivity [17]. Panneton and Olny [18] expressed the dynamic flow resistivity as a function of the material's intrinsic properties, i.e. the propagation constant (complex wave number) and characteristic impedance. The real part of the low-frequency limit of the dynamic resistivity yields the static flow resistivity (Ns/m^4) as follows [18],

$$\sigma = Re\left[\lim_{\omega\to 0}(\gamma Y_p)\right] \tag{1}$$

$$\sigma = Re\left[\lim_{\omega\to 0}(jk_p Y_p)\right] \tag{2}$$

Where, γ, k_p and Y_p are the propagation constant (m^{-1}), complex wave number (m^{-1}) and the characteristic impedance (Pa·s/m) of acoustic material, respectively.

The intrinsic properties are evaluated using the indirect acoustic methods based on standard impedance tube method, viz. the two-cavity method [14] and two-thickness method [15]. The two-cavity method involves measurement of the surface impedances for the conditions of the specimen when backed by rigid termination and an arbitrarily chosen back cavity of depth L and the complex wave number and characteristic impedance of acoustic material are evaluated as follows [12],

$$k_p = \frac{1}{2l}\tan^{-1}\left(\sqrt{\frac{Z_{22}}{Z_{11}} - \frac{Z_{12}[Z_{22}+Z_{11}]}{[Z_{11}]^2}}\right) \tag{3}$$

$$Y_p = jZ_{11}\tan 2k_pl \tag{4}$$

Where, Z_{11} and Z_{12} are the specific acoustic impedance (Pa·s/m) at the front surface of the specimen of thickness l when the specimen is backed by rigid termination and arbitrarily chosen back cavity. On the other hand, Z_{22} is the acoustic impedance at the back surface of the test specimen when backed by the arbitrarily chosen back cavity and is written as [20],

$$Z_{22} = -j\rho c \cot kL \tag{5}$$

Where, ρ is the air density (kg/m^3), c is the speed of sound (m/s), L is the arbitrarily chosen back cavity depth (m) and k is the wave number defined as $k = 2\pi f/c$, where f is the frequency.

In case of the two-thickness method, the acoustic impedances are measured at the front surface of the specimen having two different thicknesses, in which it is experimentally convenient to make second specimen thickness twice of the other. The surface impedance of the specimen is estimated from the measured pressures at two locations along the length of impedance tube using standard impedance tube technique. In this method samples are backed by rigid termination and the intrinsic properties are obtained as follows [15],

$$\gamma = \frac{1}{4l}\ln\left(\frac{1+a}{1-a}\right) \tag{6}$$

$$Y_p = \sqrt{Z_{11}(2Z_{12}-Z_{11})} \tag{7}$$

$$a = \sqrt{\frac{2Z_{12}-Z_{11}}{Z_{11}}} \tag{8}$$

Where, Z_{11} and Z_{12} are the specific acoustic impedance (Pa·s/m) at the front surface of the specimen having thickness $2l$ and $4l$, respectively.

Tao et al. [12] evaluated the specific acoustic impedances utilizing the transfer function method [19, 20, 21] based on the ISO 10534.2 standard impedance tube. Another way of evaluating impedance is to record the individual complex pressures at the two microphone locations and then utilize the analytical formulation given below,

$$Z = \rho c\left[\frac{A+B}{A-B}\right] \tag{9}$$

Where, A and B are the complex pressure amplitudes of the incident and reflected wave, respectively. Figure 1 depicts a standard impedance tube design according to ISO 10534.2.

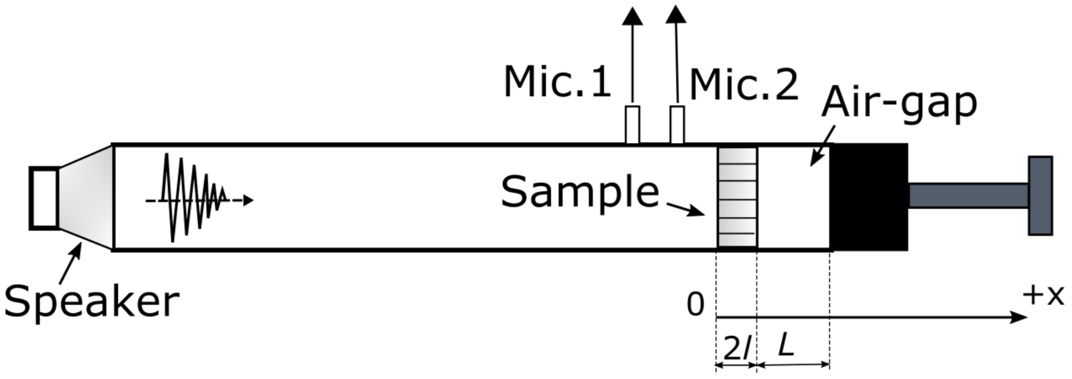

Fig. 1. ISO 10534.2 standard impedance tube

To validate the static flow resistivity results evaluated using the two-cavity and the two-thickness method, a test setup has been developed in compliance with the ISO9053 alternating airflow method guidelines. A sinusoidal alternating airflow is generated with the help of motor-driven piston cylinder arrangement at a frequency of 2 Hz. The piston movement leads to volume modulation which in turn results in pressure modulation in the vessel whose end is closed by means of a sound absorbing material. The quantity of pressure modulation is directly related to the airflow resistivity. Figure 2 depicts the schematic diagram of ISO9053 alternating airflow setup.

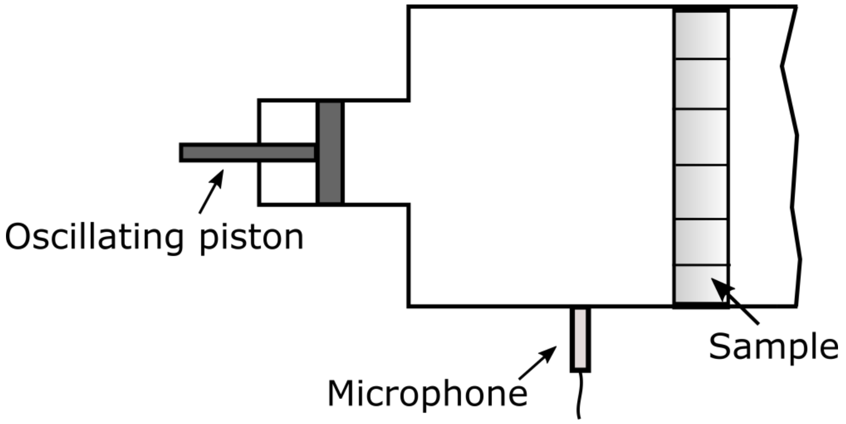

Fig. 2. Schematic diagram of ISO 9053 alternating airflow setup

Once the static flow resistivity is evaluated and validated. Then, characteristic impedance and propagation constant can be estimated using empirical equations given by Delany and Bazley [2].

$$Y_p = \rho c\left[1 + 0{,}051\left(\frac{\sigma}{f}\right)^{0{,}75}\right] - 0{,}077j\rho c\left(\frac{\sigma}{f}\right)^{0{,}73} \tag{10}$$

$$Y = jk_p = 0{,}175k\left(\frac{\sigma}{f}\right)^{0{,}59} + jk\left[1 + 0{,}086\left(\frac{\sigma}{f}\right)^{0{,}70}\right] \tag{11}$$

The surface impedance, reflection and absorption coefficient could be deduced as follows [22],

$$Z = -jY_p \cot 2k_p l \tag{12}$$

$$R = \left[\frac{Z - \rho c}{Z + \rho c}\right] \tag{13}$$

$$\alpha = 1 - |R|^2 \tag{14}$$

2. Results and discussion

Initially, the two-cavity method with arbitrary air-gap was implemented and the individual pressure measurements were carried out for foam sample at the two microphone locations. The specific acoustic impedance was analytically evaluated from the pressure measurements. The frequency range considered is 100-500 Hz by setting the microphones at wide spacing.

Fig. 3. Impedance tube foam test sample of 100 mm diameter with 22 mm thick

As per the impedance tube requirement, a 100 mm diameter foam sample is prepared from a 22 mm thick sheet. The dynamic flow resistivity for 22 mm thick foam sample subjected to 50 mm back cavity depth is depicted in Fig. 4.

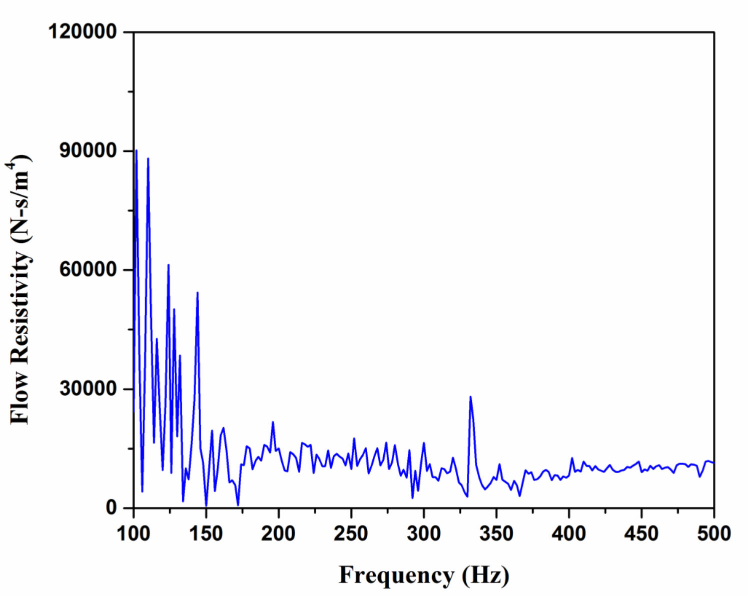

Fig. 4. Flow resistivity as a function of frequency for 22 mm thick foam subjected to 50 mm back cavity depth in two-cavity method

The value of static flow resistivity is expected to be acceptable when the measurement frequency is few hundreds of Hz or lower [12]. Due to poor signal to noise ratio below 200 Hz, the static flow resistivity was evaluated in the 200-300 Hz frequency range. The mean and standard deviation (%) of flow resistivity values for 22 mm thick foam in the 200-300 Hz range are listed in Table 1. Mean value can be considered as the static flow resistivity.

Table 1
Static flow resistivity for 22 mm thick foam in two-cavity method

Static Flow Resistivity (Ns/m^4) in 200-300 Hz frequency range		
Acoustic Material	Mean	Standard Deviation (%)
Foam	12069	25,62

Thus, the static flow resistivity results for 22 mm thick foam sample was measured using the two-cavity method with 50 mm back cavity depth. The back cavity was arbitrarily chosen and could be subject to changes depending on the availability and the experimenter's rational. Thus, it becomes very much essential, to study the effect of a change in air-gap on flow resistivity. For the same reason, the 22 mm thick foam sample was subjected to varying air-gaps; 50 mm, 100 mm and 125 mm and the flow resistivity as a function of frequency is evaluated as shown below.

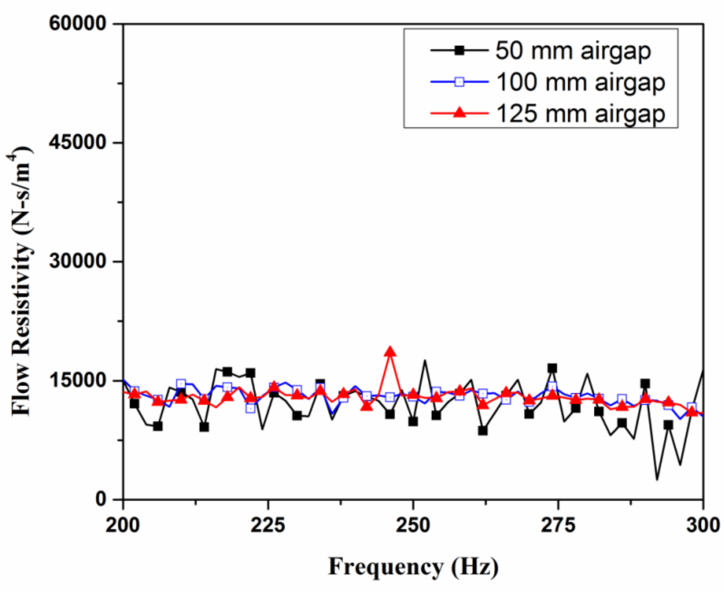

Fig. 5. Effect of change in air-gap on flow resistivity for 22 mm thick foam

From Fig. 5, it could be seen that the change in flow resistivity with respect to a change in air-gap is insignificant and the larger air-gap leads to more stable results. The same is depicted in tabular form (Table 2),

Similarly, the effect of a change in thickness of sample on measured flow resistivity is studied. Two foam samples are chosen with thickness of 22 mm and 44 mm and provided an air-gap of 50 mm in the impedance tube. The measured flow resistivity as a function of frequency is shown in Fig. 6.

Table 2
Effect of change in air-gap on static flow resistivity of foam in two-cavity method

Air Gap	50 mm	100 mm	125 mm
Static Flow Resistivity (Ns/m^4)	12069	13043	12896
Standard Deviation (%)	25,62	8,23	8,58

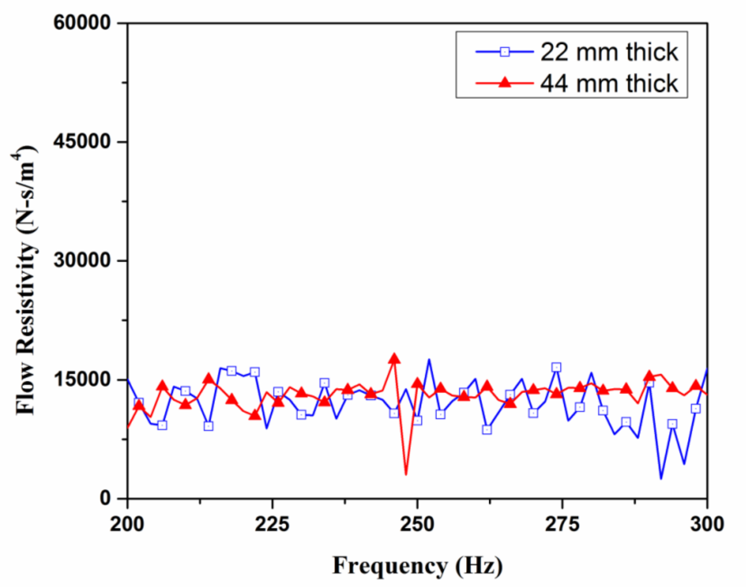

Fig. 6. Effect of change in thickness on flow resistivity of foam subjected to 50 mm back cavity depth in two-cavity method

From Fig. 6, it could be seen that the change in flow resistivity with respect to a change in thickness is insignificant and the larger thickness leads to more stable results. The measured values of static airflow resistivity for two different thicknesses are shown in Table 3. In addition, the effect of a change in air-gap and thickness on flow resistivity is summarized in Table 4.

Table 3
Effect of change in thickness on static flow resistivity and measured standard deviation of foam in two-cavity method

Thickness	22 mm	44 mm
Static Flow Resistivity (Ns/m^4)	12069	13051
Standard Deviation (%)	25,62	15,34

From Table 4, it could be seen that larger air-gap and thickness leads to improved flow resistivity results in case of foam. Also, change in either condition doesn't seem to significantly affect the mean static flow resistivity values for the implemented two-cavity method.

Table 4
Effect of change in thickness on static flow resistivity and measured standard deviation of foam in two-cavity method

Air Gap	50 mm		125 mm	
Thickness	22 mm	44 mm	22 mm	44 mm
Static Flow Resistivity (Ns/m^4)	12069	13051	12896	13304
Standard Deviation (%)	25,62	15,34	8,58	6,44

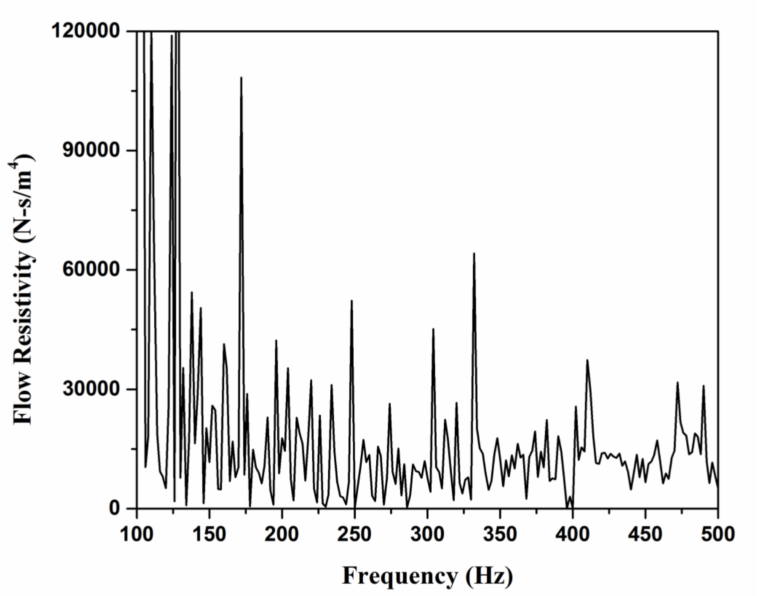

Fig. 7. Flow resistivity as a function of frequency evaluated using two thickness method for 22 mm and 44 mm thick foam in the 100-500 Hz range

The two-thickness method was also implemented for 22 mm and 44 mm thick foam samples in the 100-500 Hz frequency range. The complex impedance data was analytically evaluated from the individual pressure measurements at the two microphone locations and the dynamic flow resistivity as a function of frequency is shown in Fig. 7. It is observed that flow resistivity values in the 100-500 Hz range are fluctuating more as compared to the two-cavity method. The mean and the standard deviation (%) of the measured dynamic flow resistivity in the 200-300 Hz frequency range as chosen in the two-cavity method is listed in Table 5. Mean values is considered as static flow resistivity.

Table 5
Static flow resistivity for foam evaluated using the two-thickness method

Static Flow Resistivity (Ns/m^4) in 200-300 Hz frequency range		
Acoustic Material	Mean	Standard Deviation (%)
Foam	11357	91,68

A comparison is made between the flow resistivity values evaluated using the two-cavity method with arbitrary air-gap and the two-thickness method for foam samples in the 200-300 Hz frequency range.

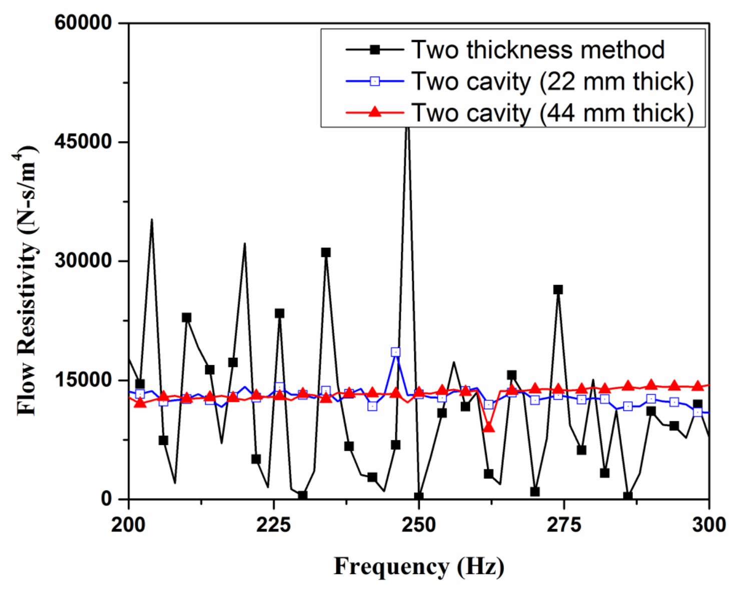

Fig. 8. Comparison of flow resistivity as a function of frequency evaluated using two-thickness and two-cavity method (125 mm back cavity depth) for foam in the 200-300 Hz range

The mean and standard deviation of the flow resistivity values in the 200-300 Hz frequency range of two methods are compared in the Table 6.

Table 6
Comparison of static flow resistivity for foam in the 200-300 Hz frequency range

Indirect Acoustic Method	Two-Thickness	Two-Cavity (125 mm air-gap)	
		22 mm thick	44 mm thick
Static Flow Resistivity (Ns/m^4)	11357	12896	13304
Standard Deviation (%)	91,68	8,58	6,44

From Table 6, the static flow resistivity evaluated using the two-thickness and the two-cavity method seems to be in good agreement. Though the mean values appear close, from Fig. 8, it could be seen that the variation in flow resistivity with respect to the frequency obtained from the two-thickness method is large as compared to the flow resistivity evaluated using the two-cavity method with arbitrary air-gap. Thus, for the foam samples (in the 200-300 Hz frequency range), it could be summarized that the implementation of the two-cavity method with arbitrary air-gap leads to a more stable trend in flow resistivity than the two-thickness method.

The static flow resistivity evaluated using the two-cavity and the two-thickness method is validated by means of the developed test setup as per the ISO 9053 alternating airflow method guidelines. The 44 mm thick foam specimen was tested using the developed setup and the airflow resistivity was measured as 10608 Ns/m^4. A comparison is made between the static flow resistivity results obtained using the two-cavity method, two-thickness method, and the developed alternating airflow test setup and shown in Table 7.

Table 7
Validation of static flow resistivity results for foam

Measurement Method	Two-Cavity (125 mm air-gap)	Two-Thickness	Alternating Airflow Setup
Static Flow Resistivity (Ns/m^4)	13304	11357	10608

From Table 7, it could be seen that the maximum difference between the static flow resistivity results obtained ranges around 25%. The acceptability of this variation could be determined based on the variation in the estimated absorption coefficient values.

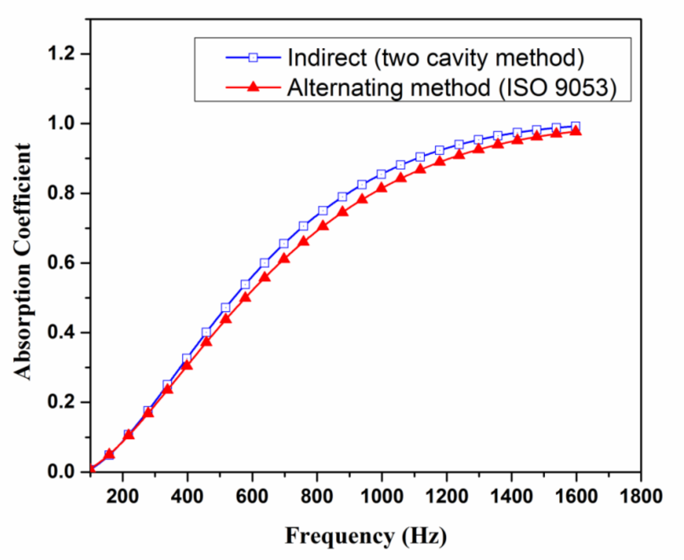

Fig. 9. Comparison of absorption coefficients estimated from flow resistivity values of 13304 Ns/m^4 (two-cavity method) and 10608 Ns/m^4 (alternating airflow method)

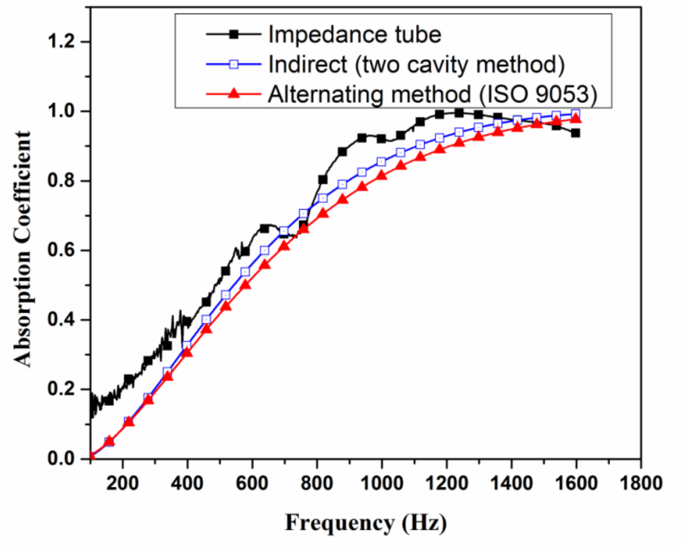

Fig. 10. Comparison of measured and estimated absorption coefficients as a function of frequency for 44 mm thick foam

The Delany and Bazley empirical relations are used to estimate the absorption coefficients from the flow resistivity values given in Table 7, and are shown as a function of frequency in Fig. 9. It could be seen that the estimated absorption coefficients are in good agreement despite the 25% variation in the static flow resistivity values. This indicates that the 25% variation may be reasonable for estimation of absorption coefficient. The absorption coefficients for the 44 mm thick foam sample are also directly measured using the impedance tube and the results are compared with the estimated absorption coefficients. The measured and estimated absorption coefficients seem to be in good agreement from Fig.10.

Conclusions

The two-cavity method with arbitrary air-gap and the two-thickness method were implemented for evaluation of characteristic impedance and propagation constant and hence flow resistivity for foam samples in the 100-500 Hz frequency range. The flow resistivity was found to be constant, i.e. static in the 200-300 Hz range and hence the post-analysis was carried out considering this frequency range. In case of a two-cavity method with arbitrary air-gap, the effect of a change in air-gap and thickness on mean static flow resistivity was insignificant. Larger air-gaps and thicknesses resulted in a more stable trend in flow resistivity plot as a function of frequency. The static flow resistivity values evaluated using the two-cavity and the two-thickness method for foam in the 200-300 Hz range was found to be in reasonable agreement. Though the mean values appear close for the two methods, the variation in flow resistivity with respect to frequency for the two-thickness method was significantly large as compared to the two-cavity method. The flow resistivity results were validated using a test setup developed based on ISO 9053 alternating airflow method guidelines and the maximum variation was in the range of 25%. This variation was found to be acceptable due to a close agreement between the absorption coefficients estimated from the flow resistivity values using the Delany and Bazley empirical relations. In addition, the estimated absorption coefficients for foam samples were found to be in good agreement with the absorption coefficients directly measured using the impedance tube, thus indicating good suitability and feasibility of the considered static flow resistivity measurement methods.

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