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THE EFFECT OF AIR GAP THICKNESS ON SOUND ABSORPTION COEFFICIENT OF POLYURETHANE FOAM

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ABSTRACT

Polyurethane foam is widely used in noise control engineering to absorb sound. This paper investigates the effect of air gap thickness behind polyurethane foam on the sound absorption coefficient for low and high frequency sounds using the impedance tube method. The polyurethane foam test samples were prepared with thickness of 25 mm, with two different diameters; 29 and 100 mm for high (1.0 to 6.4 kHz) and low (100 Hz to 1.6 kHz) frequency measurements respectively. The foam was subjected to microscopic observation under an optical microscope for pore size analysis. It was observed that the sample has a honeycomb structure with the majority of pores' diameters being less than 1 mm. The measurement was carried out for six different air gap thicknesses; 0, 5, 10, 15, 20 and 25 mm. The results showed that introducing an air gap behind the sample influences the sound absorption coefficient, which increased especially for higher frequency sounds until the optimum value was obtained. It also showed that the frequency of maximum peaks for varying air gap thicknesses was different, with the peaks for larger air gap thicknesses shifting towards lower frequencies. However, this combination of polyurethane foam and air gap was not able to absorb low frequency sounds, especially below than 250 Hz.

Keyword: *Acoustical material; polyurethane foam; air gap thickness; sound absorption coefficient; impedance tube.*

1. INTRODUCTION

The applications of noise control are at present given significant priority in various industries, such as automotive, manufacturing and ship building. It plays an important role in creating an acoustically pleasant environment. This can be achieved when the intensity of sound is reduced to a certain level that is not harmful to human ears. Various techniques can be applied for this, which employ different kinds of materials. One such technique is using acoustical materials to absorb sound

(Gracia-Valles *et al*., 2008; Yang & Wu, 2011; Jaouen & Becot, 2011). These acoustical materials are available in the market as fibrous or porous materials, and in various types, such as nonwovens, fibrous glass, mineral wools and foams (Ersoy & Kucuk, 2009; Arenas & Crocker, 2010; Kino & Ueno, 2007). Generally, all these types of materials are made from polymeric or rubber based materials, due to low cost of production and their flexibility, making it easy to cut and form into complex shapes. However, for acoustical materials in high temperature applications, such jet engines, most of them are made from ceramics that are hard and fire resistant (Zhang *et al*., 2006; Cuiyun *et al*., 2012; Fuji *et al*., 2006).

The main function of acoustical materials is to reduce the acoustic energy of sound waves that pass through it (Figure 1). This can be performed using resistive materials that consist of porous structure which change sound energy into heat. This can happen when energy is changed due to frictional forces between sound waves and the cell walls in the pore structure (Fang *et al*., 2007). In other words, the further the distance sound waves travel through the medium of porous structure, the higher the amount of sound energy which is dissipated. From the reduction of sound energy, it can be assumed that this energy is being absorbed by the acoustical materials. Therefore, the amount of sound energy that is absorbed represents the sound absorption characteristics which describe performance of the acoustical materials.

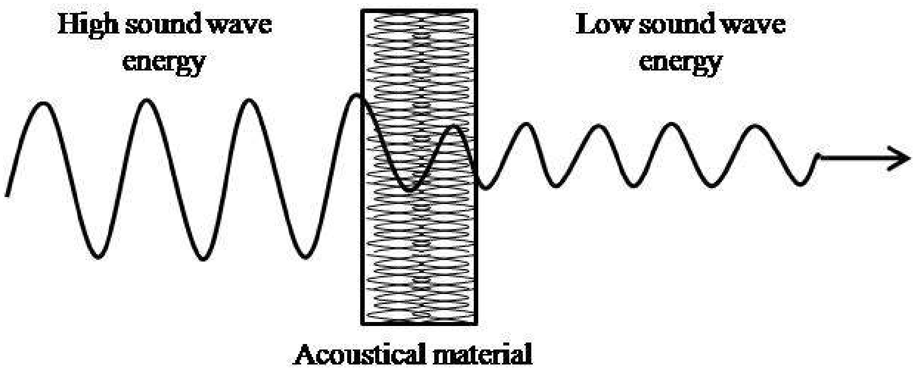

Figure 1: High sound wave energy is reduced after passing through the acoustical material.
(Source: Bies & Hansen, 2009)

In practice, there are two methods used to install acoustical materials; either using an air gap or not. It can be attached directly, or some air gap thickness can be created from the wall. The methods of installing acoustical materials play an important role in improve noise absorption. By introducing an air gap behind an acoustical material any residues of incident sound waves that are not absorbed or transformed into heat energy after transmission through the acoustical material will face additional resistance through the air medium. The mechanism of sound waves dissipating in the air medium is known as the Helmoltz resonance effect. It excites some of the sound waves' frequencies, causing them to oscillate at greater amplitude. When the energy reaches the maximum level, the sound waves become weak due to friction with air particles, which converts sound energy into heat (Zhang *et al*., 2012; Norton & Karszub, 2003; Crocker, 2007).

Previous studies show that the combination of acoustical materials and air gap thickness has significant impacts on the sound absorption coefficient. Rosli *et al*. (2009) reported that the air gap layers within the coir fibre sound absorption panels improve the sound absorption coefficient for medium and high frequencies. Seddeq (2009) found that the sound absorption coefficient increases when plastic fibre absorbers are associated with air gap. The advantage of installing acoustical materials with air gaps is to reduce costs by maintaining the thickness of the acoustical materials while improving the sound absorption coefficient.

This study is aimed at investigating the effect of air gap thickness on the sound absorption coefficient of polyurethane foam. It is a porous type of acoustical material which has been widely used in many applications, including construction, automotive, machinery and electronics. Even though polyurethane foam is excellent for noise control applications, not much attention has been provided on the combination of polyurethane foam with air gaps. The findings of this study demonstrate that adding an air gap behind polyurethane foam improves it sound absorption coefficient for high frequencies applications.

2. METHODS FOR EVALUATING THE PERFORMANCE OF ACOUSTICAL MATERIALS

There are two different methods available to evaluate the performance of acoustical materials, which are reverberant room and impedance tube (Sagartzazu *et al*., 2007; Ingard, 2010; Doutres, 2010). In general, the measurement is to study the effects of exposure of materials to known sound fields. Both methods are able to collect the properties of sound absorption materials, such as sound absorption coefficient, reflection coefficient and surface impedance. Sound absorption coefficient is the property that is most referred to by engineers and scientists in evaluating acoustical environments (Crocker, 2007). By looking at the value of the sound absorption coefficient, the ability of acoustical materials to absorb the sound energy can be predicted, and it is used in calculation at early stage of design. The reverberant room method needs expensive measuring equipment, a qualified acoustician and a large size of samples (Scien, 2011; Bies & Hansen, 2009). Therefore, this method is limited and cannot be expanded upon due to the high costs involved in setting up the facility and preparing the samples.

In the impedance tube method, the test sample is tested within a rigid tube, in which the sound is internally guided, forced to propagate along the tube's axis and hits the back plate (Crocker, 2007). Figure 2 shows the schematics of the impedance tube method. In general, the main components of the impedance tube are a loudspeaker, two microphones of 0.25 in and back plate. The loudspeaker placed at one of the tube end creates a sinusoidal pressure disturbance that propagates down the tube with the test sample positioned at the other end of tube near the back plate. The back plate's function is to reflect the incident waves and to hold the sample in the proper position. Its position is unfixed and is moveable if the measurement is carried out for air gap environments. The two microphones are in fixed positions and both of them measure simultaneously the incident wave before the sound wave enters the test sample, and reflected wave after the sound waves propagates through the test sample, hits the back plate and travels back towards the loudspeaker. The signals of incident and reflected waves from the microphones are analysed using a signal analyser based on the transfer function method. Using this method, the ratio of reflected and incident waves is obtained, which represents the sound absorption coefficient of the acoustical material (Doutres, 2010).

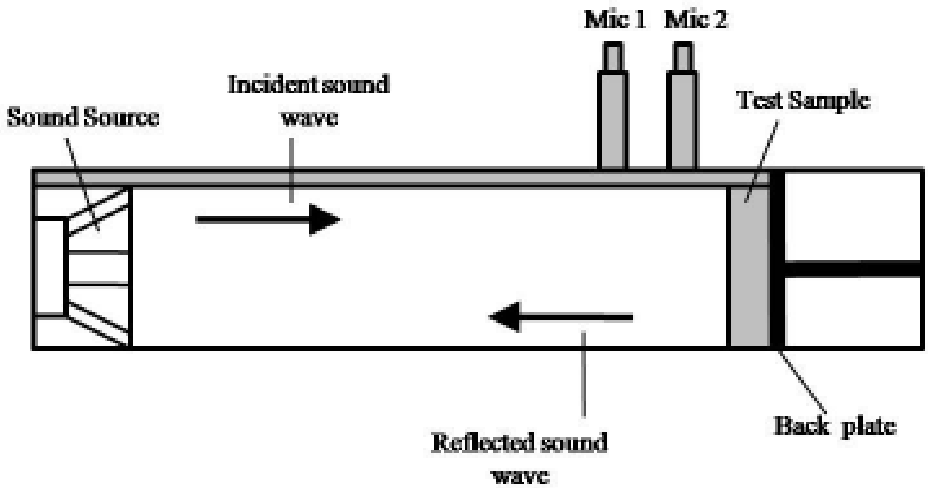

Figure 2: Schematic of the impedance tube method.
(Source: Crocker, 2007)

Most of the measurements for sound absorption coefficient are carried out using two tubes of different diameters; large and small diameters for low and high frequency sound respectively. Both measurement and design of the impedance tubes are according to the international standards, which are ISO (1998) and JIS (2007). According to Crocker (2007), to ensure that only plane waves, with no transverse waves, enter tube, the lengths of the tubes shall exceed 0.25λ, while the diameters shall not exceed 0.58λ, where λ is the wavelength of sound in air. For example, tubes with diameter of 100 mm and length of 910 mm are useful for sounds in the range 90 Hz to 1.8 kHz. In order to conduct the measurement over the range of 90 Hz to 6.0 kHz, two different tube sizes are required. Therefore, many of the impedance tube products available in the market have a large tube of 100 mm diameter for low frequency sounds and a small tube of 29 mm diameter for high frequency sounds. Based on the diameters of the tubes, the frequency ranges are 100 Hz to 1.6 kHz and 1.0 to 6.4 kHz for low and high frequency sounds respectively. However, as the frequency range between 1.0 to 1.6 kHz is repeated for both the low and high impedance tubes, variations of the results may exist. Therefore, in order to increase accuracy, many researchers suggest that the values of sound absorption coefficient be computed based on the averages of the measured data.

In the impedance tube, which is a close boundary system, the calculations are made based on the assumption that the propagation of the waves is in 1D direction. Therefore, only plane waves propagate in the tube. The calculations of the sound absorption coefficient using the impedance tube method have been established and described in many publications (Crocker, 2007; Hansen, 2009). The calculations are quite complex and are based on the transfer function method. To simplify these calculations, the sound absorption coefficient α is the ratio between intensities of reflected and incident waves, and can be expressed as:

$$\alpha = 1 - \frac{I_r}{I_i} \tag{1}$$

where I_r and I_i are the intensities of the reflected and incident waves respectively. If the ratio uses the spectrum of fast Fourier transform (FFT), it can be expressed as:

$$\alpha = 1 - \frac{S_{bb}}{S_{aa}} \tag{2}$$

where S_{bb} and S_{aa} are the FFT spectrums of the reflected and incident waves respectively.

The value of α is usually expressed in the range of 0 and 1. A material that absorbs all incident waves will have α = 1. On the other hand, if α = 0, no energy of sound is absorbed. Therefore, this material also can be called an insulation material and if it is backed with a rigid wall, all the incident waves will be fully reflected by the material (Crocker, 2007).

3. METHODOLOGY

The test apparatus was part of a complete acoustical material testing system from Scien Co. (Figure 3). In this system, a loudspeaker placed at one end of tube generates a broadband random signal from 100 Hz to 6.4 kHz. The sample was placed at the end of the impedance tube in front of the back plate. Two fixed microphones were located vertically on the tube, with the distances from the loudspeaker being 150 and 170 mm for microphones 1 and 2 respectively. The microphones were of the 0.25 in free-field type from SIEN Co., which were used to measure incident and reflected sound waves in the impedance tube respectively. For data acquisition and signal processing, an embedded power amplifier, a four-channel SCIEN Co Vibro-Acoustic ADC 3241 signal platform and a desktop computer equipped with Acoustic Duct Version 9291-4.3E software were used.

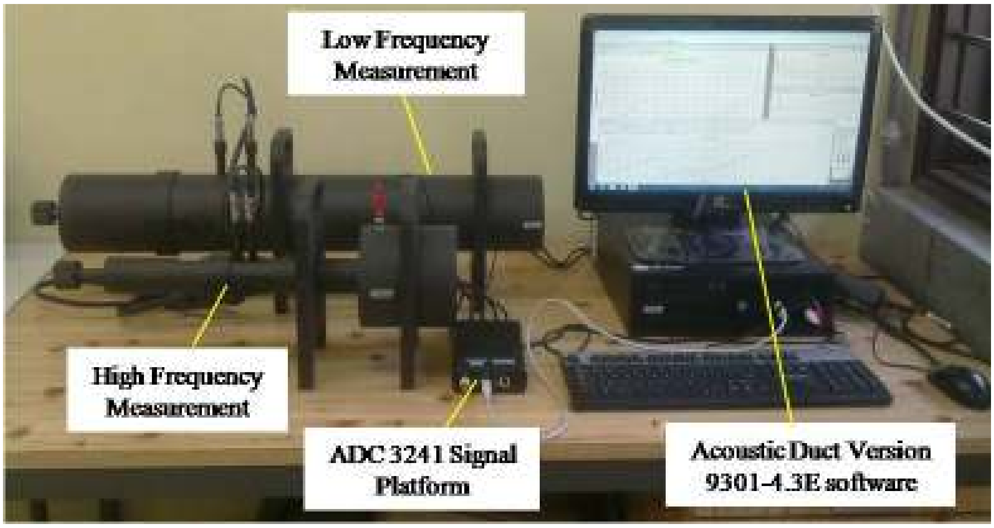

Figure 3: The Scien Co. impedance tube measurement system was used in this study.

The polyurethane foam sample was subjected to macroscopic observation under a Carl Zeiss Stemi DV4 optical stereo microscope and the image was analysed using the Axio Vision KS 400 software. For the sound absorption coefficient measurement, test samples were prepared in two different diameters, 29 and 100 mm for high and low frequency measurements respectively (Figure 4). The thickness of samples was fixed at 25 mm. For the measurement of sound absorption coefficient with air gap thickness, the study was carried for six different air gap thicknesses, which were 0, 5, 10, 15, 20 and 25 mm. Figure 5 shows the setup of air gap thickness, which is the separation between the back plate and test sample that creates a cavity.

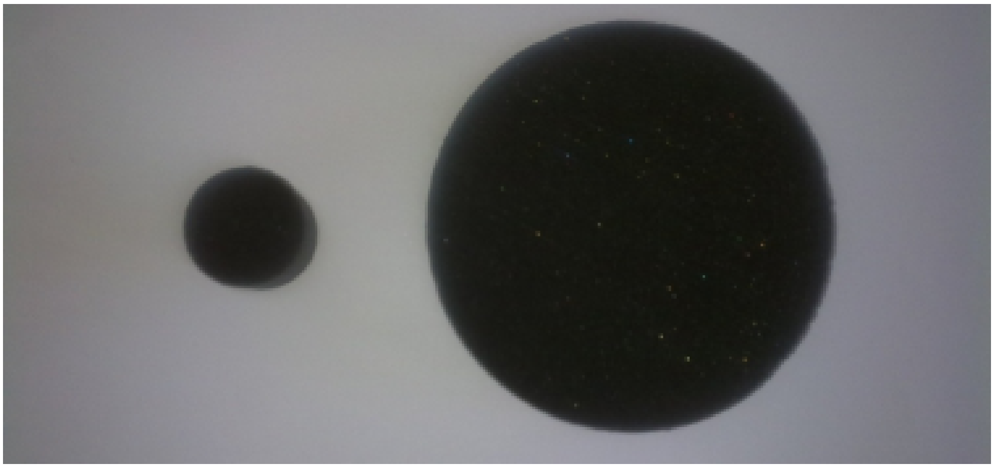

Figure 4: The prepared of polyurethane foam test samples with two different diameters; 29 mm for the small foam on the left and 100 mm for the large foam on the right.

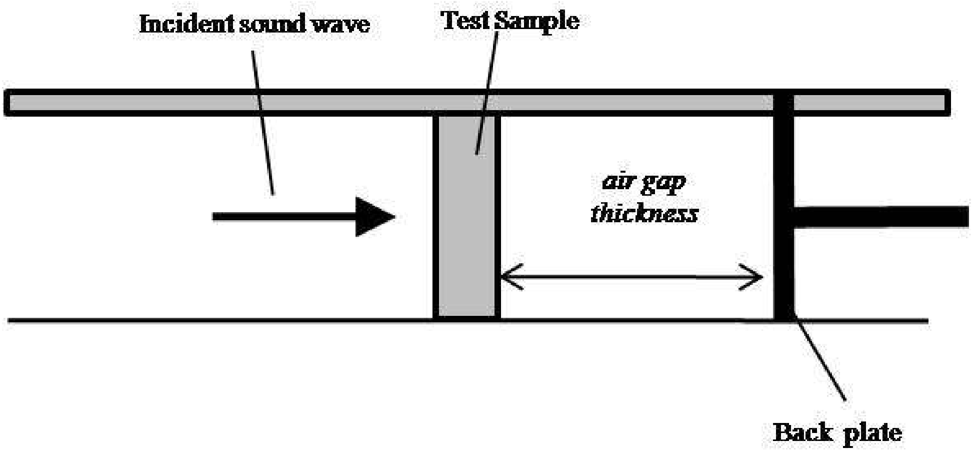

Figure 5: The separation between the back plate and test sample that creates a cavity which represents air gap thickness.

4. RESULTS & DISCUSSION

The observation using the optical microscope (Figure 6) shows that the structure of the polyurethane foam sample is pore cells with honeycomb structure. The pore cells are interconnected to each other with multiple pore cell sizes. The bright areas in the image correspond to the pores, whereas the dark areas correspond to the open holes. Detailed examination of the image shows that the majority of the pores' diameters are less than 1 mm.

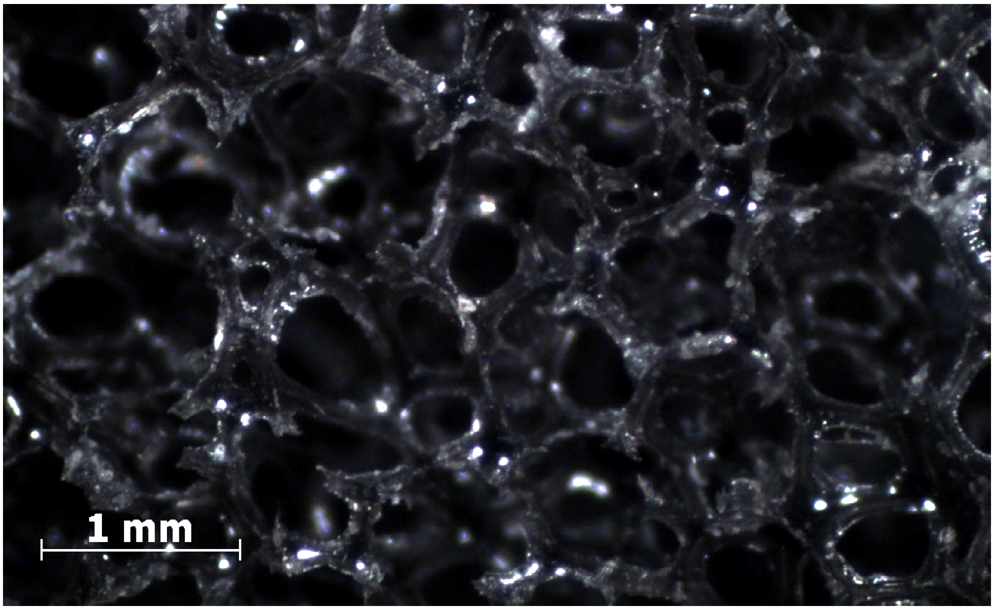

Figure 6: Image of the porous polyurethane foam captured using an optical microscope.

Figure 7 shows the correlation between sound absorption coefficient and wave frequency for the different air gap thicknesses. It can be seen that the properties of sound absorbing characteristics of polyurethane foam vary significantly with wave frequency. All the plots show the same trend, which is low sound absorption coefficients at low frequencies, and high sound absorption coefficients at high frequencies.

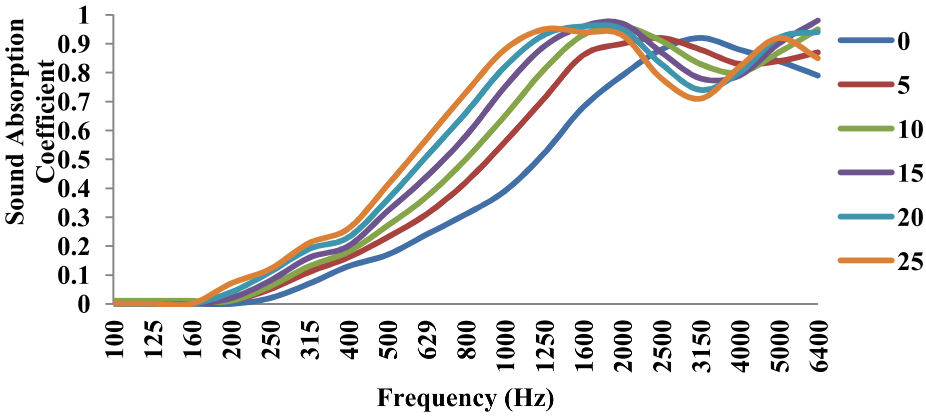

Figure 7: Sound absorption coefficients of polyurethane foam with different air gap thicknesses.

The plot for polyurethane foam without air gap shows the maximum peak value of sound absorption coefficient of 0.92 at frequency of 3.15 kHz. As the frequency is increased, the values of absorption decrease. For the case of polyurethane foam with different of air gap thicknesses, the plots show two different peaks which are maximum and minimum respectively. The maximum peaks occur at medium frequencies, while minimum peaks occur at higher frequencies. As compared with the peak of the plot without an air gap, all the peaks of the plots with air gaps are shifted towards to lower frequencies with higher thicknesses of air gap showing lower values. The value of maximum peak of each plot does not show much difference with most of the peaks being close to 1, with the range of 0.05. This low range indicates that the sound absorption coefficient is not affected by air gap thickness. The highest value obtained is 0.97 for air gap thickness of 15 mm. The minimum peaks for all the plots with air gaps occur at high frequencies, with the lowest value being 0.78 for air gap thickness of 25 mm. All the plots also show that the absorption coefficient value drops between frequencies of 2 to 3.15 kHz after reaching the maximum peak, except for the sample with air gap thickness of 25 mm, where there is another drop at frequency of 5 kHz.

For the analysis of sound absorption coefficients of the polyurethane foam with and without air gap, the values obtained indicate that both methods are efficient in absorbing sound waves at high frequencies, particularly above 250 Hz. However, for the polyurethane foam with air gaps, all the plots show the improvements of the sound wave frequencies that are being absorbed. For very low frequencies, below 250 Hz, the results show that sound absorption coefficient with value of zero is obtained. This indicates that both methods are not able to absorb the incident waves and fully reflected after hitting the back plate. According to Zhang *et al*. (2012), low frequency sounds are very difficult to absorb because of their long wavelength. As a result, the total of sound waves energy remaining constant. This phenomenon is in good agreement with the principle of conservation of energy (Giordano, 2010). Therefore, in any isolated or closed system, the sum of all forms of energy remains constant. It can be concluded that the polyurethane foam with thickness of 25 mm, with and without air gaps used in this study are unable to absorb low frequency sound waves, and hence, is inefficient for low frequencies applications. In order to improve the reduction of low frequency sounds, the acoustical materials used should be thicker in order to provide enough time for sound waves to form into heat when travelling through the obstacles within the acoustical materials (Seddeq, 2009; Norton *et al*., 2003).

The mechanism of sound waves dissipated in air medium is due to the Helmoltz resonance effect (Zhang et al, 2012; Norton et al, 2003; Crocker, 2007). The peaks of resonance frequencies can be clearly seen in the Figure 7, which correspond to the maximum sound absorption coefficient at these frequencies. However, the sound absorption coefficient at certain frequencies is reduced after reaching the maximum peak. This phenomenon occurs due to sound waves propagation within the air medium, where the excitation and degradation of sound energy depend on the thickness of air gaps (Ayub *et al.*, 2009; Zhang & Tianning, 2009; Fouladi *et al.*, 2010). Even though the sound absorption coefficient is reduced, the values obtained are still high, with most of them above than 0.8.

5. CONCLUSION

Microscopic observation showed that the polyurethane foam acoustical material used in this study is porous with honeycomb structure. The results of the analysis showed that the majority of diameters of the pores are less than 1 mm. The sound absorption coefficient of polyurethane foam with six different air gap thicknesses of 0, 5, 10, 15, 20, and 25 mm were studied and validated through experimental measurements in an impedance tube measurement system. Sound absorption coefficient for both with and without air gaps significantly increased with increase of sound wave frequencies, until the maximum peak was obtained. All the maximum peaks of the plotted of air gap thicknesses shifted with the lowest frequency obtained for larger air gaps. The results also showed that the air gaps reduced the sound absorption capability at high frequencies of sound waves. Both methods, with and without air gap, were not able to absorb the low frequencies of sound waves, particularly below than 250 Hz. The implementation of combination polyurethane foam with air gaps was able to enhance the sound absorption coefficient in the medium frequency range without changing the thickness of acoustical materials.

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