The Combined Effects of Thermal and Acoustic Parameters on the Sound Absorption of Aluminum Foam Panels

Tawfeeq W. MOHAMMED
College of Engineering, Mustansiriyah University, Iraq,
tawfeeqwasmi@uomustansiriyah.edu.iq

Abstract: - In a foamed panel, the sound absorption is influenced by several design parameters related mostly to acoustic features. This study has gathered the combined effects of thermo-acoustical parameters on sound absorption in aluminum foam panels. These parameters include pore size, porosity, relative density, flow resistivity, frequency, air temperature and pressure. The sound absorption coefficient has been calculated theoretically based on a reliable approach. The results have shown high absorption values for the aluminium foam (Al-foam) because of its low relative density. The values ranged from 0.75 for a relatively high-density panel and small pore size to 0.87 for a relatively low-density and medium pore-size board.

Furthermore, the absorption values have decreased by increasing the temperature and pressure. The air temperature increase by 25 °C reduced the absorption by 2-4% at constant pressure. Specifically, the values of sound absorption coefficient at 10 bar and 100 °C were less by 10-15% compared to that obtained at standard atmospheric conditions.

Keywords: - aluminum foam, sound absorption, acoustic, thermal, insulation.

1. INTRODUCTION

Metal foam is composed of rigid metal and pores of gas or air simply. The air usually occupies more than 80% of the composite. The foaming structure of the metal is required in many applications. These applications may require lightweight strength with the ability to absorb the sounds and the vibrations. These foams are also fire retarding and easy to recycle. Aluminum foams are either open cells where the pores connect partially or closed cells without connection. The cells have different shapes as polygon, hexagonal and square. The open-cell mode is required for acoustic absorption and damping of the impact energy. The closed-cell type is beneficial in structural applications because of its superior mechanical properties to those of open-cell metal foams [1]. However, foamed metals are strong materials which offer a high aspect ratio (surface to volume). The interesting mechanical features of aluminum foams (Al-foams) are related to the fully isotropic response. Other advantages include low thermal conductivity and corrosion resistance [2]. Aluminum foams have been interested in many applications related to structural, thermal and acoustic components [3-5]. In specific, the main applications of aluminum foams included the benefit of their lightness, strength and ability of sound and impact resistance besides heat transfer purposes. The presence of pores within metallic foam gives the ability to absorb considerable impact energy and acoustic waves. Porosity and foamed structure enable the metal to act as acoustic proofing and impact absorber for vehicles and machines [6-15].

Many studies have presented the contribution of Al-foams in applications related to sound absorption, impact damping and their acoustic parameters. Navacerrada et al. (2013) [16] have studied thermal properties and sound absorption features. The Al/NaCl composite has been exposed to an infiltration process to form high porosity and homogenous distribution foam. The diameters of the cells under consideration ranged from 0.5-2 mm. The foam used for the acoustic tests had a 100 mm diameter and 20 mm thickness under frequencies ranging from 100-6500 Hz. The air resistivity values ranged from 5-10 kPa.s/m^2. These features allow for high sound absorption, especially at low-frequency values.

The results show that 0.5 mm cell diameter had the best sound absorption (up to 0.8). Byakova et al. (2014) [17] have presented an effective method to manufacture closed-cell foams assigned for sound absorption purposes. The foaming agent was TiH_2. Heat treatment is necessary, especially near the solidification point and rapid cooling by quenching. A perforating process is required to ensure sufficient acoustic absorption. The diameter of the cells under consideration was approximately 1 mm. The thicknesses of the panels were 10 and 15 mm with relative density between 0.2-0.3. The range of frequencies was up to 1000 Hz. The results show that the sound absorption coefficient (SAC) can be reached up to 0.8 at a relative density of 0.24. Guan et al. (2015) [18] have introduced a study for the influential factors in acoustical attenuation due to the shape and design of Al-foam with semi-open cells using a neural network model. The study evaluated the effect of bulk density and static flow resistivity on absorption performance. Results have shown that the density has less impact on the coefficient of absorption performance. The key factor was the flow resistivity, which has relatively critical implications. This impact was more effective beyond 1000 Hz, where the increase in the resistivity led to a high absorption coefficient for Al-foam up to 0.84. Analysis has shown good reliability for the suggested model to predict the acoustic absorption properties. Azizan et al. (2017) [19] investigated the sound absorption properties of the open-cell aluminum foam produced by infiltration casting. The size of the cells was in the range of 1-3 mm. The acoustic features were measured using an impedance tube instrument, where the sound absorption coefficient was determined. Generally, when the sound frequency was high (more than 800 Hz), Al-foam gave a higher sound absorption (more than 0.8) for bigger pore size.

Arjunan et al. (2019) [20] have presented a method to evaluate the acoustic parameters of metallic foams. Al-foams have served in the investigation to analyze the acoustic parameters, but the study has reported nickel foams and copper foams as superior sound absorption panels. The study has also referred to the impact of dimensions and pore sizes on the results. Yan et al. (2020) [21] have investigated to study the impact response of Al-foam integrated with corrugated sandwich panels. In the study, a sandwich panel with corrugated cores has been integrated by adding closed-cell Al-foam. The structure is expected to have a higher energy absorption capacity. It has been reported that the traditional panel was less energy absorption than that integrated by the metallic foam. Opiela et al. (2021) [22] have studied the acoustic absorption of perforated closed-cell Al-foams.

The goal was to evaluate the acoustic parameters of perforated metals. The experimental works depended on the sound absorption test using the impedance tube. The results also encouraged sound absorption values that were validated by comparing the data with reliable sources. Mettan et al. (2021) [23] have suggested a theoretical procedure to obtain foams with desired pore size (diameters of the cells ranged from 0.1-1 mm). A validation by X-ray scanning has been utilized to follow the growth of the bubbles. Some critical parameters were sought during the study, such as resistivity, heat conductance and Seebeck coefficient. The data encouraged using the obtained foam for many applications related to electrical, thermal and acoustic appliances with frequencies up to 30 kHz. Lin et al. (2022) [24] conducted in-site noise reduction tests in highway tunnels using an Al-foam panel. The results were analyzed, showing that the Al-foam was sufficient in reducing the noise for a specific frequency range below 1000 Hz. Furthermore, the sound transmission loss test for the Al-foam panel has recorded 4 dB less than the reference level.

Previous studies show that Al-foams are active in sound attenuation due to their high absorption, especially at low to medium frequencies. In this context, open-cell foams perform better than closed-cell in sound absorption. In general, the absorption coefficient for Al-foam is between 0.2-0.9 and flow resistivity is less than 20 kPa.s/m^2 [25]. However, these studies have not focused on the air properties, such as temperature, pressure and corresponding thermo-physical properties, since they are also effective parameters in the acoustic design [26-28].

Therefore, the contribution of the current study is to investigate the thermal-acoustical interfacial effects on the values of SAC. The goal is to see how far the air properties affect the final absorption value besides other design parameters such as porosity, relative density and pore size.

2. MATERIALS AND METHODS

The compound effect of thermal properties (temperature, density and pressure) with acoustic parameters (porosity and flow resistivity) on the sound waves through a medium can be represented by the term"thermo-acoustic". This study aims to evaluate thermo-acoustical parameters that affect the acoustic performance of an Al-foam panel for a certain thickness. The sound absorption coefficient (SAC) is the indication of material's absorptivity, and it is calculated by many analytical approaches. Initially, it is important to denote some parameters related to porous media, such as relative density, porosity and flow resistivity. Relative density is the ratio between the densities of both bulk (porous) and solid materials, as:

$$RD = \frac{\rho_{bulk}}{\rho_{solid}} \tag{1}$$

The porosity is the air volume ratio inside the panel to the total volume occupied by the bulk material. Can be expressed as [19]:

$$\varphi = (1 - RD) \times 100\% \tag{2}$$

The resistivity of the flow inside the porous media depends mainly on the porosity. In the literature, several empirical formulas estimate air-flow resistivity based on many variables, such as relative density, binder concentration, compaction ratio, porosity, etc. An expression extracted from Maderuelo-Sanz [29] can be used to calculate the resistivity (σ) in (Pa.s/m^2) as:

$$\sigma = 53000 - 634\,\varphi \tag{3}$$

In the current study, the sound absorption coefficient is calculated based on the approach introduced by Delany [30] and Allard [31]. The calculation depends on the physical characteristics of the material and the air inside the panel designed for acoustic absorption. Researchers and engineers often use this method because of the accuracy and simplicity of predicting the acoustic performance of the board by calculating absorption coefficient values. This method has the benefit of its flexibility, in which the relationship depends on the thermo-physical properties of the medium. The analysis usually calculates acoustic impedance at specific frequencies for a continuous period. It can be widely used in porous materials with a wide range of flow resistivity [32, 33].

The sound absorption coefficient (α) is given by [19, 20]:

$$\alpha = \frac{4\,SWR}{(SWR+1)^2} \tag{4}$$

The standing wave ratio (SWR) is given by;

$$\text{SWR} = \Gamma / \rho\, C \tag{5}$$

where;

Γ: Surface impedance factor.

ρ: Air density.

The speed of sound (C) is a function of air temperature, and it is given by:

$$C = \sqrt{\gamma R T} \tag{6}$$

where;

γ: Ratio of specific heats of air.

R: gas constant.

T: Air temperature.

The specific heats of the air are various, and they depend on the pressure and the temperature, as shown in Table 1.

Table 1. Variation of air features [34]

Pressure (bar)	Temp. (°C)	Ratio of specific heats	Gas constant (J/kg.K)
1	25	1.400	287.7
	50	1.399	287.4
	75	1.398	287.2
	100	1.397	287.1
5	25	1.416	298.2
	50	1.408	295.5
	75	1.404	292.3
	100	1.402	290.4
10	25	1.430	309.4
	50	1.419	303.2
	75	1.412	298.3
	100	1.407	294.1

Since air is a compressible fluid at high speeds, hence the density of air is related to pressure and temperature as:

$$\rho = \frac{P}{RT} \tag{7}$$

Now, the following acoustic parameters are used in the calculation [30]:

$$Z = \rho\, C\left[\left\{1 + C_1\left(\frac{f\rho}{\sigma}\right)^{C_2} - i\left[C_3\left(\frac{f\rho}{\sigma}\right)^{C_4}\right]\right\}\right] \tag{8}$$

$$\varepsilon = K\left\{C_5\left(\frac{f\rho}{\sigma}\right)^{C_6} + i\left[1 + C_7\left(\frac{f\rho}{\sigma}\right)^{C_8}\right]\right\} \tag{9}$$

where: f is the frequency, while σ is the flow resistivity.

The wave number (K) can be found by:

$$K = 2\pi f / C \tag{10}$$

The values of acoustic factors (C1-C8) are listed in Table 2.

Table 2. Coefficients used in theoretical approach [20]

C1=0.0570	C2=-0.745	C3=0.0870	C4=-0.732
C5=0.1890	C6=-0.595	C7=0.0978	C=-0.700

Hence, the surface impedance can be found as [30]:

$$\Gamma = Z \coth(\varepsilon t) \tag{11}$$

where (t) is the foam thickness. Note that the effect of pore size (d) appears within the definition of porosity, which represents the volume of pores to the total volume of the panel.

3. RESULTS AND DISCUSSIONS

The results are valid for the operational conditions shown in Table 3. The thickness of the foam panel (t) is 5 cm, which is required in the calculation. The density of the solid aluminum is considered as 2.7 g/cm^3. Figure 1 is a schematic drawing showing the pore dimensions and the distribution within the panel. Note that the evaluation of SAC is assumed for normal incidence across the closed-cell panel.

Table 3. Operational conditions

Parameter	Range of values
Pore size (d)	0.5-2 mm
Wall thickness (t_w)	(0.25-1.0) d
Relative density (RD)	0.2-0.5
Porosity (φ)	50-80%
Resistivity (σ)	2-21 kPa.s/m^2
Air pressure (P)	1-10 bar
Air temperature (T)	25-100 ˚C
Frequency (f)	100-2100 Hz

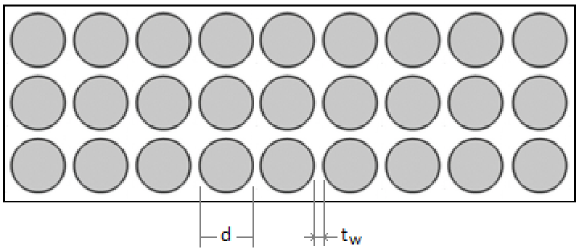

Figure 1. A scheme for pore dimensions and distribution

To recognize the effect of acoustic and thermal parameters, it is preferable first to discuss each band of selective parameters separately and then observe them together to evaluate the combined effect.

3.1. Acoustical parameters

The absorption coefficient values at different frequencies have been theoretically determined for different pore sizes and corresponding relative densities, as shown in Figures 2-4. These values were calculated at standard air conditions (atmospheric pressure and room temperature). The behaviour of the results tends to record high α-values (up to 0.8) for the Al-foam because of its low relative density. The α-values have improved from 0.75 for the panel, which has a relatively high density of 0.5 and a small pore size of 0.5 mm, to 0.87 for the board, which has a relatively low density of 0.3 and medium pore size of 1 mm. The standard values at high relative density are due to the low porosity and high flow resistivity.

On the other hand, the reason for low values at small pore sizes is due to the difficulty of sound waves passing through narrow passages, which decreases the role of the viscous effect in absorbing sound energy [19]. Thus, the optimum choice would be RD=0.3 with d=1 mm. This gives an air-flow resistivity of 8 kPa.s/m^2. The resistivity value recommended by this study is under that mentioned by [16], where below five kPa.s/m^{2,} the acoustic absorption is insufficient due to the high sound transmission, and the material is too compact above ten kPa.s/m2.

The α-values from the analytical approach show increasing with the increase of the frequency, where the absorption rises due to the high dissipation of acoustic energy as a result of both viscous loss and thermal loss from the continuous collision by the wall of the cells along the way inside the panel. For 1 mm pore size, the peak α-values were: 0.82 at 1500 Hz, 0.87 at 1500 Hz, 0.85 at 1700 Hz and 0.77 at 1900 Hz for RD=0.2, 0.3, 0.4 and 0.5 respectively. The observer can note that when the frequency goes higher than 1000 Hz, the absorption coefficient increases significantly toward 0.8. This is also mentioned by [18]. Furthermore, between 100-700 Hz, the difference in α-values is minimal, which is recognized by [20], when the values were too close for frequencies below 800 Hz.

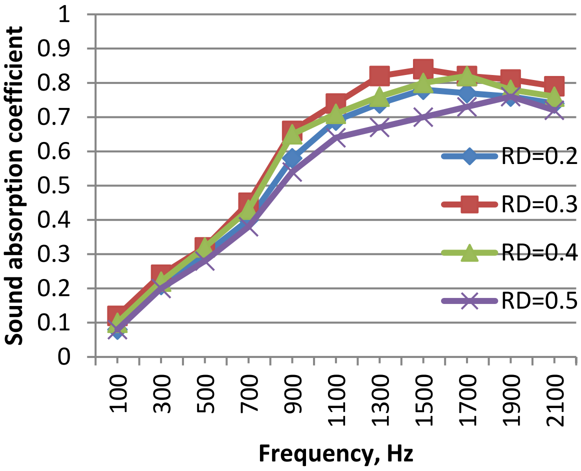

Figure 2. Variation of SAC for different densities, d=0.5 mm, P=1 bar, T=25 ºC

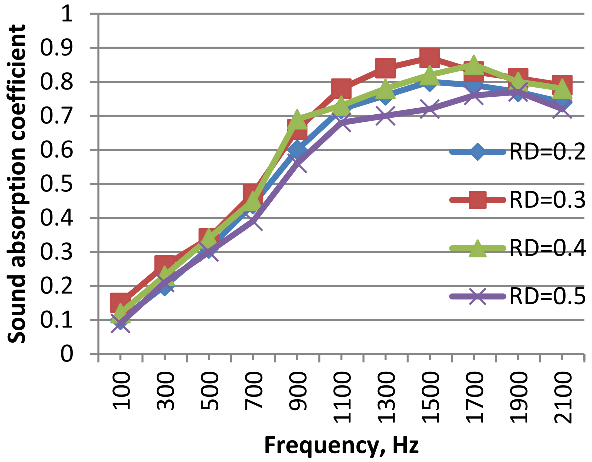

Figure 3. Variation of SAC for different densities, d=1 mm, P=1 bar, T=25 ºC

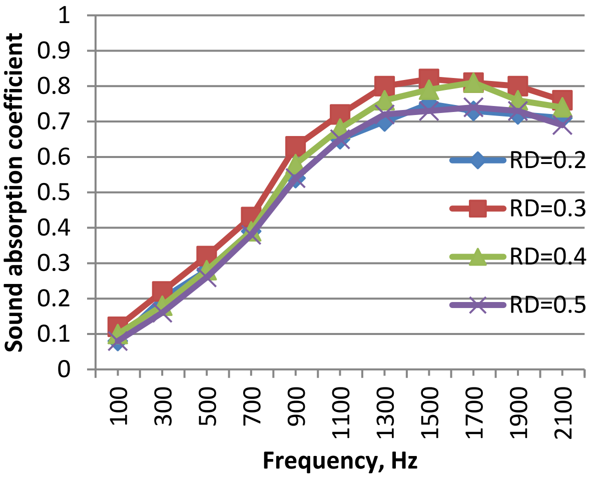

Figure 4. Variation of SAC for different densities, d=2 mm, P=1 bar, T=25 ºC

3.2. Thermal parameters

In this perspective, the characteristic of Al-foam was fixed at a relative density of 0.3 and pore diameter of 1 mm. The values of maximum absorption coefficients at specific pressure and temperature under consideration are shown in Figure 5. It can be seen that maximum α-values can be recorded at low temperatures and pressure. The increase of air temperature by 25 ºC has generally reduced the α-value by 2-4% at constant pressure. Even though the variation in SAC was not so high, it can be more effective with the combined influences of other physical parameters. Also, Bainamndi et al. [26] have revealed that the effect of temperature is insignificant below 50 ˚C.

Furthermore, the increase of air pressure by 5 bar has reduced the α-value by 1-3% at constant temperature. Notice that at high pressure (10 bar), the effect of temperature difference was slight. However, Wang et al. [28] have mentioned that sound absorption for porous metal behaves variously under high pressure depending on the density, porosity, frequency and thickness.

Moreover, a correlation is extracted for the maximum value of SAC at specific pressure and temperature, which is related to the reference values of air approximately, as follows:

$$\alpha = \alpha_o - \frac{1}{1000}(T - T_o) - \frac{1}{500}(P - P_o) \qquad (12)$$

where: α_o is the maximum absorption coefficient at atmospheric pressure and room temperature.

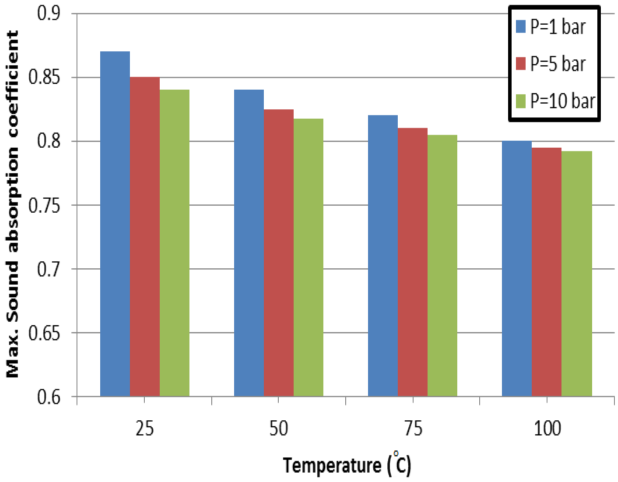

Figure 5. Values of maximum SAC at different air features, d=1 mm, RD=0.3

3.3. The combined effects

The sound absorption coefficient of Al-foam is based predominantly on porosity and corresponding acoustical parameters [35]. It has also been affected by the thermo-physical properties of airflow. Hence, the current study finds the combined effect of thermal and acoustic parameters. By analyzing the results, it can say that Al-foam is suitable for acoustic insulation at standard air conditions (atmospheric pressure and room temperature). The increase in air pressure and temperature decreases the absorption coefficient. This decrease has not had that precious impact on the overall absorption at the optimum design (RD=0.3 and d=1 mm) unless the air temperature was very high. Note that the increase in air pressure has less effect. However, when the relative density is higher than 0.3, or the pore size is smaller than 1 mm, the combined influences become more effective, as shown in Table 4, where the values of reduction in maximum SAC were: 10, 12 and 15% for cases 1, 2 and 3, respectively.

Table 4. The combined effects for certain cases

Case	Design parameter	Pressure and temperature	Max SAC
1	RD=0.3, d=1 mm	1 bar, 25 °C	0.87
	RD=0.3, d=1 mm	10 bar, 100 °C	0.78
2	RD=0.3, d=0.5 mm	1 bar, 25 °C	0.85
	RD=0.3, d=0.5 mm	10 bar, 100 °C	0.75
3	RD=0.5, d=1 mm	1 bar, 25 °C	0.76
	RD=0.5, d=1 mm	10 bar, 100 °C	0.65

3.4. Comparison with other studies

For validation purposes, the data used or obtained in the current study have been compared with that mentioned in other studies, as shown in Table 5. Most of these studies cover a very close range of design parameters, even if they change the types of Al-foams or the methods. The resultant values of maximum SAC are within 0.6-0.8 and mainly occurred at frequencies between 1000-1500 Hz. However, there is also some variation (about 10%), which is attributed to both: the accuracy of theoretical assumptions and errors in the experimental readings.

Table 5. Comparing the data between current and previous works

Study	Description	Dimensions	Design parameters	Frequency	Max SAC
Current	Theoretical work to study the combined effect of thermo-acoustical parameters on SAC.	t=5 cm closed-cell d=0.5-2 mm	RD=0.2-0.5 φ=50-80% σ=2-21 kPa.s/m^2	f≤2100 Hz	0.75-0.87 @ 1500-1800 Hz
[16]	Experimental work to study the thermal and acoustical properties.	t=2-4 cm open-cell d=0.5-2 mm	RD=0.1-0.2 φ=80-90% σ=5-20 kPa.s/m^2	f≤6500 Hz	0.80-0.90 @ 1000 Hz
[17]	Experimental work to improve sound absorption by heat treatment.	t=1-2 cm closed-cell d=1 mm	RD=0.2-0.3 φ=70-80%	f≤1000 Hz	0.70-0.80 @ 1200 Hz
[18]	Theoretical work to study the SAC using neural networks.	semiopen-cell d=0.4-1 mm	RD=0.3-0.4 φ=60-70% σ=28-140 kPa.s/m^2	f≤2000 Hz	0.67-0.84 @ 1600 Hz
[19]	Theoretical work to study the SAC at high frequency.	open-cell d=1-3 mm	RD=0.3-0.6 φ=30-60%	f≤5000 Hz	0.80 @ 800-1000 Hz
[20]	Study the influence of design parameters on SAC in general	t=1-5 cm closed-cell d≤3 mm	RD≤0.15 φ≥80%	f≤2000 Hz	0.60 @ 800-1400 Hz
[21]	Evaluate the energy absorption for composite Al-foam/PU sandwich panel	Required data are not available.			
[22]	Experimental work to improve sound absorption using perforated closed-cell.	closed-cell d=1-2 mm	RD=0.2 φ=80%	f≤6400 Hz	0.80 @ 1600 Hz and 0.85 @ 3500 Hz
[23]	Provide a method to justify the cell size in Al-foam.	Required data are not available.			
[24]	Measuring the noise reduction due to the use of Al-foam in traffic tunnels.	t=1 cm closed-cell d=5 mm	RD≤0.4 φ≥60%	f≤2000 Hz	0.40-0.80 about 1000 Hz

4. CONCLUSIONS

This study looks closely at the combined effect of thermo-acoustical parameters on sound absorption in aluminum foam panels. The results generally revealed high absorption values, except for panels with relatively high-density panels or small pore sizes. The absorption values have decreased slightly by increasing the temperature and pressure, but this reduction can be effective for uncontrolled design. Numerically, the peak values of SAC were between 0.7-0.8 for the selected cases. The optimum SAC value was 0.87 at 1500 Hz (RD=0.3 and d=1 mm at atmospheric conditions). These values were less by 10-15% at 10 bar and 100 °C.

ACKNOWLEDGMENTS

The author thanks the College of Engineering - Mustansiriyah University (Iraq).

REFERENCES

[1] Sara F., Graziano U., Al-Based Metal Foams, Retrieved on July 18, 2022, from https://encyclopedia.pub/entry/6194

[2] Goodfellow, Aluminium Foam – Structure, Properties and Benefits, AZoM, Retrieved on July 16, 2022 from https://www.azom.com/article.aspx?ArticleID=10529

[3] Sinha N., Srivastava V., Sahoo K., Processing and application of aluminium foams, In CAFP-2008, Special Metal Casting and Forming Processes, 25-26 Feb 2008, India, 2012, 54-63.

[4] García-Moreno F., Commercial applications of metal foams: Their properties and production, *Materials*, 9, 85, 2016.

[5] Fernandez-Morales P., Nieto C., Patiño C., Lopez J., Tamayo D., Mendoza E., Giraldo M., A conceptual design of energy exchange system for recovery of residual heat using aluminium foams, Proceeding of 8th International Conference on Porous Metals and Metallic Foams, 23-26 Jun 2013, USA, 2014, 371-376.

[6] Rajak D., Kumaraswamidhas L., Das S., Technical overview of aluminium alloy foam, *Rev. Adv. Mater. Sci.*, 48, 2017, 68-86.

[7] Rajak D., Gupta M., An Insight Into Metal Based Foams: Processing, Properties and Applications, 1st ed., Springer, 2020.

[8] Baumeister J., Lehmhus D., Weise J., Aluminum foams - processing, properties, and applications, In the book: ASM Handbook: Aluminum Science And Technology, ASM, 2018.

[9] Garai F., Modern applications of Aluminium foams, *International Journal of Engineering and Management Sciences (IJEMS),* Vol. 5, No. 2, 2020.

[10] Farhadi S., Kafili D., Ziadloo S., Review of aluminium foam applications in architecture, *European Journal of Engineering Science and Technology*, 1, 2020, 62-70.

[11] Patrick H., Daniel R., Hansgeorg B., Derivation of motivators for the use of aluminium foam sandwich and advantageous applications, International Conference on Engineering Design (ICED21), 16-20 Aug, Sweden, 2021.

[12] Khare S., Sorte M., An overview of aluminium foam production methods, *IJESC*, Vol. 11, No. 02, 2021, 27659-27666.

[13] Baiocco G., Tagliaferri V., Ucciardello N., Neural networks implementation for analysis and control of heat exchange process in a metal foam prototypal device, 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering (ICME), 20-22 Jul 2016, Italy, 2017.

[14] Banhart J., García-Moreno F., Heim K., Seeliger H., Lightweighting in transportation and defence using aluminium foam sandwich structures, International Symposium on Light Weighting for Defence, Aerospace and Transportation, November 11 2017, India, 2017.

[15] Chen S., Bourham M., Rabiei A., Applications of open-cell and closed-cell metal foams for radiation shielding, 8th International Conference on Porous Metals and Metallic Foams, 23-26 Jun 2013, USA, 2014, 293-298.

[16] Navacerrada M., Fernández P., Díaz C., Pedrero A., Thermal and acoustic properties of aluminium foams manufactured by the infiltration process, *Applied Acoustics*, Vol. 74, No. 4, 2013, 496-501.

[17] Byakova A., Gnyloskurenko S., Bezimyanniy Y., Nakamura T., Closed-cell aluminium foam of improved sound absorption ability: Manufacture and properties, *Metals*, 4, 2014, 445–454.

[18] Guan D., Wua J., Wub J., Li J., Zhao W., Acoustic performance of aluminium foams with semiopen cells, *Applied Acoustics*, 87, 2015, 103–108.

[19] Azizan M., Ismail M., Salleh N., Natarajan D., Sound absorption properties at high sound frequency of open cell aluminium foam, *Journal of Mechanical Engineering*, Vol. SI 2, No. 1, 2017, 161-173.

[20] Arjunan A., Baroutaji A., Praveen A., Olabi A., Wang C., Acoustic Performance of Metallic Foams, In book: Reference Module in Materials Science and Materials Engineering, Elsevier, 2019.

[21] Yan L., Yu B., Han B., Zhang Q., Lu T., Lu B., Effects of aluminium foam filling on the low-velocity impact response of sandwich panels with corrugated cores, *Journal of Sandwich Structures & Materials*, Vol. 22, No. 4, 2020, 929-947.

[22] Opiela K., Zielinski T., Dvorak T., Kudela Jr., Perforated closed-cell aluminium foam for acoustic absorption, *Applied Acoustics*, Vol. 174, 107706, 2021.

[23] Mettan X., Martino E., Rossi L., Jaćimović J., Krsnik J., Barišić O., Babcsán N., Beke S., Mokso R., Kaptay G., Forró L., Acoustic-pressure-assisted engineering of aluminium foams, *Adv. Eng. Mater.*, 23, 2100306, 2021.

[24] Lin Z., Gong W., Wan L., Shen J., Zhang H., Huang J., Zhu B., Field measurements for traffic noise reduction in highway tunnels using closed-cell aluminium foam board, *Applied Sciences*, 12, 538, 2022.

[25] Mohammed T., Al-Jaafari M., Atea I., Aluminum foams as metal/ceramic composites and their morphological, thermo-physical and mechanical properties: a review study, *Journal of Industrial Mechanics*, Vol. 7, No. 3, 2022, 8-23.

[26] Bainamndi D., Siryabe E., Doka S., Ntamack G., High-temperature effect on absorption coefficient of M-MPPs and sandwich structures coupled with MPPs, *Open Journal of Acoustics*, 10, 2020, 1-18.

[27] Zhou B., Zhang J., Li X., Liu B., An investigation on the sound absorption performance of granular molecular sieves under room temperature and pressure, *Materials*, 13, 1936, 2020, 1-12.

[28] Wang X., Li Y., Chen T., Ying Z., Research on the sound absorption characteristics of porous metal materials at high sound pressure levels, *Advances in Mechanical Engineering*, Vol. 7, No. 5, 2015, 1-7.

[29] Maderuelo-Sanz R., Morillas J., Martín-Castizo M., Escobar V., Gozalo G., Acoustical performance of porous absorber made from recycled rubber and polyurethane resin, *Latin American Journal of Solids and Structures*, 10, 2013, 585–600.

[30] Delany M., Bazley E., Acoustical properties of fibrous absorbent materials, *Applied Acoustics*, Vol. 3, No. 2, 1970, 105-116.

[31] Allard J., Atalla N., Porous materials with perforated facings, Chapter in the book: Propagation of Sound in Porous Media, Springer, 2009.

[32] Attenborough K., Models for the acoustical characteristics of air-filled granular materials, *Acta Acust*, No. 1, 1993, 213-226.

[33] Dazel O., Numerical Methods for the Biot Theory in Acoustics, University of Maine, Laboratory of Acoustics - UMR CNRS 6613, 2011.

[34] Cengel Y., Boles M., Thermodynamics-An Engineering Approach, 8th ed, McGraw Hill, 2015.

[35] Nosko M., Simančík F., Florek R., Tobolka P., Jerz J., Mináriková N., Kováčik J., Sound absorption ability of aluminium foams, *Metallic Foams*, Vol. 1, No. 1, 2017, 15-41.