Prediction of the Acoustic and Thermal Performance of a Multilayer Partition

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Abstract

Multilayer partitions are often designed so that, because of their peculiar composition or structure, they exhibit characteristics that are not normally found in single layer panels. "Multifunctional" partitions are engineered to optimize different features at the same time. In this paper the authors try to deal with the problem of optimizing thermal and acoustic behavior by designing a thermo-acoustic insulation structure. From the thermal point of view, the material should combine good insulation properties, given by low thermal conductivity, and high delay of the thermal wave due to external conditions, given by low thermal diffusivity. From the acoustic point of view, the material should have good absorption characteristics, whenever possible, and primarily high transmission loss in order to respect the relevant law prescriptions. In this way the composite panel, used as a façade element, can improve the comfort conditions in buildings and reduce energy consumption for winter heating and summer cooling. The coupled thermo-acoustic element is made of different wooden and recycled material layers, chosen for their specific properties and sustainable characteristics. Thermal properties were estimated by means of a self-developed code based on the ISO 13786 standard. The acoustic properties of the individual layers, according to the ASTM E2611-09 standard procedure, were measured in a four-microphone impedance tube, and the transfer matrix method was used to estimate the overall acoustic behavior of the material. Particular attention was paid to the layer sequence, because of great importance for both thermal and acoustic performances. The preliminary combined study showed encouraging results.

1. Introduction

As stated by the European directive 2010/31/UE on the energy performance of buildings (European Parliament, 2010), buildings account for 40% of total energy consumption in the European Union. Therefore, the energy performance of buildings should be improved, taking into account outdoor climatic conditions and indoor climate requirements. According to the guideline, all the member States should take the necessary measures to ensure that minimum energy performance requirements are set for buildings and building units or building elements that constitute the building envelope and have a significant impact on its energy performance every time they are replaced or retrofitted. The limits should be set with the aim of achieving cost-optimal levels (Tronchin et al., 2014). The study of unconventional materials such as phase-change materials to fulfill winter and summer requirements (see for instance Neri et al., 2020) is also of broad and current interest.

The European directive 2010/31/UE came into force in Italy with the introduction of the Ministerial Decree (DM) of 26 June 2015 (Italian Ministry of Economic Development, 2015). This law classifies the types of building renovations, distinguishing between major first-level renovations, major second-level renovations and energy upgrading interventions. Major renovations are defined as those involving the elements of the building envelope with an incidence higher than 25% on the overall area. Major first-level renovations involve the building envelope with an incidence of more than 50% of its overall area and the renovation of the heating system and/or the cooling system of the entire building. In such cases the energy performance requirements

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are applied to the entire building. Major second-level renovations involve the building envelope with an incidence of more than 25% of the overall area of the building and may affect the heating system and/or the cooling system. In such cases, the energy performance requirements relate to the thermo-physical characteristics of the portions and the dimensions of the elements and components of the building envelope involved in the energy renovation. Finally, energy upgrading interventions are all the other interventions with an impact on the energy performance of the building. These interventions therefore involve an area that is less than or equal to 25% of the overall area of the building, and/or involve the heating and/or cooling system. In such cases, the energy performance requirements apply only to the building components and installations involved. The DM 26 June 2015 also establishes the requirements for the different cases.

In terms of the envelope consisting of opaque vertical components of existing buildings undergoing renovation – which is the object of this work – in the case of major first-level renovations the value of the overall heat transfer transmission coefficient H'_T have to fulfil the limit value of 0.73 W/m^{2}K for the climatic zones A and B, 0.70 W/m^{2}K for the climate zone C, 0.68 W/m^{2}K for the climate zone D, 0.65 W/m^{2}K for the climate zone E and 0.62 W/m^{2}K for the climate zone F; moreover, for locations where the average monthly irradiance value on the horizontal plane in the month of maximum summer insolation is greater than or equal to 290 W/m^2, for all the opaque vertical walls with the exception of those included in the northwest / north / northeast quadrant, it is required that the value of the surface mass M_s is greater than 230 kg/m^2, or that the value of the periodic thermal transmittance Y_{ie} is lower than 0.10 W/m^{2}K. In the case of major second-level renovations, the value of the overall heat transfer transmission coefficient H'_T has to respect the limit values indicated above; moreover, the thermal transmittance U must comply with limit values, which will become stricter starting from 2021 (0.40 W/m^{2}K for the climate zones A and B, 0.36 W/m^{2}K for the climate zone C, 0.32 W/m^{2}K for the climate zone D, 0.28 W/m^{2}K for the climate zone E and 0.26 W/m^{2}K for the climate zone F). In the case of energy upgrading interventions only the limit values of the thermal transmittance U have to be respected.

Thermal coatings are frequently used to enhance the energy performance of existing buildings. They consist of an insulating layer applied to the outer surface of the wall and are more efficient than internal insulation systems because they significantly reduce the thermal bridges. Since a thermal coating is usually designed to improve thermal insulation, it can also improve summer thermal behavior if it makes it possible to significantly reduce and delay the transmission inside the building of the temperature peak reached on its outer surface during the central hours of the day. Therefore, in this work some solutions are proposed, taking into account both the effect of the transmittance U and of the periodic thermal transmittance Y_{ie}. For the thermal transmittance U the obtained values have been compared with those suggested in the cases of major second-level renovations and of energy upgrading interventions, whereas for the periodic thermal transmittance Y_{ie} the reference value is 0.10 W/m^{2}K in the case of major first-level renovations.

For a multilayer partition, the thermal transmittance U depends upon the properties of the layers while the periodic thermal transmittance Y_{ie}. depends also upon the sequence of the layers. The most influencing material properties are the thermal conductivity λ and the thermal capacity C. The thermal transmittance U represents the insulation of the building and can be determined by the electrical analogy in steady heat transfer conditions. The periodic thermal transmittance Y_{ie} refers to the dynamic behavior of the partition and is especially relevant for summer performances. The dynamic thermal characteristics of a building component describe its thermal behavior when it is subject to variable boundary conditions, such as a variable heat flow rate or a variable temperature. The ISO 13786 standard (ISO, 2017a) considers only time-dependent sinusoidal boundary conditions and makes it possible to define the periodic thermal conductance, which is a complex number relating cyclic heat flow rate to cyclic temperature variations. In the case of one dimensional heat flow, valid for walls consisting of flat homogeneous layers, it is possible to define the thermal admittance, relating specific heat flow rate to temperature variations on the same side of the component, and the periodic thermal transmittances, relating specific heat flow rate to temperature variations on the two sides of the component. In particular, the internal thermal admittance is defined as $Y_{ii} = q''_i/T_i$, where T_i is a sinusoidal function and T_e is constant, the external thermal admittance is defined as $Y_{ee} = q''_e/T_e$, where T_e is a sinusoidal function and T_i is constant, and the periodic thermal transmittance is defined as $Y_{ie} = -q''_i/T_e$, where T_e is a sinusoidal function and T_i is constant. As prescribed by the ISO 13786 standard, the value of Y_{ii}, Y_{ee} and Y_{ie} can be determined from the elements of the heat transfer matrix $\mathbf{Z}_{ee} = \mathbf{Z}_{se} \cdot \mathbf{Z} \cdot \mathbf{Z}_{si}$ where $\mathbf{Z}_{se}$ and $\mathbf{Z}_{si}$ are the heat transfer matrices of the boundary layers and $\mathbf{Z}$ is the transfer matrix of a multi-layer component from surface to surface:

$$\begin{bmatrix} T_e \\ q''_e \end{bmatrix} = \begin{bmatrix} Z_{ee11} & Z_{ee12} \\ Z_{ee21} & Z_{ee22} \end{bmatrix} \begin{bmatrix} T_i \\ q''_i \end{bmatrix} \tag{1}$$

The elements of $\mathbf{Z}_{si}$ and $\mathbf{Z}_{se}$ depend on the surface resistance of the boundary layer, including convection and radiation, and should be determined in accordance with the ISO 6946 standard (ISO, 2017b):

$$\boldsymbol{Z}_s = \begin{bmatrix} 1 & -R_S \\ 0 & 1 \end{bmatrix} \tag{2}$$

$\mathbf{Z}$ is obtained by multiplying the heat transfer matrices of the N layers of the component $\mathbf{Z} = \mathbf{Z}_N \cdot \mathbf{Z}_{N-1} \cdot \ldots \cdot \mathbf{Z}_3 \cdot \mathbf{Z}_2 \cdot \mathbf{Z}_1$ where, as a convention, layer 1 is the innermost layer. The elements of $\mathbf{Z}_1$, $\mathbf{Z}_2$, …, $\mathbf{Z}_N$ depend on the thickness, the thermal conductivity and the thermal capacity of the layers by means of the expressions listed in the ISO 13786 standard. For each layer,

$$\boldsymbol{Z} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \tag{3}$$

where

$$Z_{11} = Z_{22} = \cosh\left(\frac{d}{\delta}\right)\cos\left(\frac{d}{\delta}\right) + j\sinh\left(\frac{d}{\delta}\right)\sin\left(\frac{d}{\delta}\right) \tag{4}$$

$$Z_{12} = -\frac{\delta}{2\lambda}\left\{\sinh\left(\frac{d}{\delta}\right)\cos\left(\frac{d}{\delta}\right) + \cosh\left(\frac{d}{\delta}\right)\sin\left(\frac{d}{\delta}\right) + j\left[\cosh\left(\frac{d}{\delta}\right)\sin\left(\frac{d}{\delta}\right) - \sinh\left(\frac{d}{\delta}\right)\cos\left(\frac{d}{\delta}\right)\right]\right\} \tag{5}$$

$$Z_{21} = -\frac{\lambda}{\delta}\left\{\sinh\left(\frac{d}{\delta}\right)\cos\left(\frac{d}{\delta}\right) - \cosh\left(\frac{d}{\delta}\right)\sin\left(\frac{d}{\delta}\right) + j\left[\sinh\left(\frac{d}{\delta}\right)\cos\left(\frac{d}{\delta}\right) + \cosh\left(\frac{d}{\delta}\right)\sin\left(\frac{d}{\delta}\right)\right]\right\} \tag{6}$$

Here, d is the thickness of the layer, λ is its thermal conductivity and δ is its periodic penetration depth computed as $\delta = [86400 \times \lambda / (\pi \times C)]^{1/2}$ for a period of 24 h.

This method allows the evaluation of thermal transmittance U and periodic thermal transmittance Y_{ie} for building components consisting of homogeneous layers. Standards ISO 6946 and ISO 13786 describe how to estimate U and periodic thermal conductances L_{ie} ed L_{ei} for components made of inhomogeneous layers, where inhomogeneities act as thermal bridges. Analytical and neural methods to determine the strength of such thermal bridges have been proposed by several authors (Benedetti et al., 2019; Luscietti et al., 2014; Tenpierik et al., 2008).

When dealing with comfort in buildings, acoustic quality must also be taken into account. In particular, there are two main properties which need to be considered: the attitude of the material to dissipate sound energy, expressed through the sound absorption coefficient α, and the sound insulation capability, represented by the sound transmission loss TL, which is related to the sound transmission coefficient τ through the formula $TL = 10\log_{10}(1/\tau)$. Different types of tests, such as reverberation room and standing wave tube, make it possible to obtain these parameters. The impedance tube is a double standing wave tube equipped with four microphones. It can be used to estimate only the normal incidence parameters, but it has the advantage of requiring the use of a small sample of material and of simultaneously providing further valuable information, such as the propagation wavenumber, the characteristic impedance and the speed of sound in the tested specimen. Moreover, the impedance tube, combined with the transfer matrix method, can establish the correlation between the state variables on the two sides of the sample,

$$\begin{bmatrix} p_0 \\ u_0 \end{bmatrix} = \begin{bmatrix} \Theta_{11} & \Theta_{11} \\ \Theta_{11} & \Theta_{11} \end{bmatrix} \begin{bmatrix} p_d \\ u_d \end{bmatrix} = \boldsymbol{\Theta} \begin{bmatrix} p_d \\ u_d \end{bmatrix} \tag{7}$$

where p is the sound pressure and u the particle velocity, 0 and d subscripts indicate, respectively, the front and back surfaces of the sample, referring to the direction of the incident sound wave, and Θ_{ij} are the elements of the transfer matrix. This method is particularly convenient for the acoustic characterization and optimization of complex layered structures, whose total transfer matrix, and, consequently, acoustic properties, can be obtained as the product of the individual transfer matrices in the correct sequence (Lee and Xu, 2009):

$$\boldsymbol{\Theta}_{\text{total}} = \boldsymbol{\Theta}_1 \cdot \boldsymbol{\Theta}_2 \cdot \ldots \cdot \boldsymbol{\Theta}_N \quad (8)$$

When using the impedance tube to estimate the transmission loss, one must consider that the resulting TL can be assumed to be independent of boundary conditions only for materials which are considered as an equivalent fluid, that is their shear modulus is negligible (Feng, 2013). In the case of rigid panels, the transfer matrix can be written as

$$\boldsymbol{\Theta}_p = \begin{bmatrix} 1 & Z_p \\ 0 & 1 \end{bmatrix} \quad (9)$$

so that the actual boundary conditions are taken into account through direct measurements and gathered in the acoustic impedance of the material, Z_p. The latter parameter can be calculated as $Z_p = j\omega M_s \times [1 - (1 + j\eta) \times (f/f_c) \times \sin^2 \vartheta]$, where M_s is the mass per unit area of the panel, η is the loss factor, f_c is the critical frequency, that is defined for a homogeneous plate as $f_c = c^2 \times (2\pi)^{-1} \times (M_s/D_p)^{1/2}$, with D_p bending stiffness per unit width.

2. Materials and Methods

In accordance with the ISO 6946 standard, the thermal transmittance U of the multilayer partition was determined as

$$U = (R_{S1} + R_1 + R_2 + \cdots + R_N + R_{S2})^{-1} \quad (10)$$

where R_1, R_2, …, R_N are the thermal conductive resistances of the individual layers obtained by the ratio between the thickness and the thermal conductivity of each layer, whereas R_{s1}, R_{s2} are the surface resistances of the boundary layer, including convection and radiation.

In accordance with the ISO 13786 standard, the periodic thermal transmittance Y_{ie} was determined from the elements of the heat transfer matrix from environment to environment $\mathbf{Z}_{ee}$ as

$$Y_{ie} = -\frac{1}{Z_{ee12}} \quad (11)$$

The ASTM E2611 standard procedure (ASTM, 2017) establishes the use of a four-microphone impedance tube (Fig. 1). At one endpoint of the tube a loudspeaker is installed and generates a wide-band white noise test signal. The specimen is located in a test sample holder in the central section of the tube, between two microphone pairs. The second end of the tube can be equipped with either anechoic or reflecting termination.

With reference to Fig. 1, by comparing signals from four microphones it is possible to decompose the resulting sound wave field into forward and backward travelling waves on either side of the specimen. The incident and reflected fractions, denoted as A, B, C, D in Fig. 1, are used to compute the elements of the transfer matrix according to the expressions provided by standard ASTM E2611. Finally, the absorption coefficient α (hard-backed) is obtained as

$$\alpha = 1 - \left|\frac{\Theta_{11} - \rho c \Theta_{21}}{\Theta_{11} + \rho c \Theta_{21}}\right|^2 \quad (12)$$

and the sound transmission loss TL (anechoic-backed) can be expressed as:

$$TL = 20\log_{10}\left|\frac{\Theta_{11} + \left(\frac{\Theta_{12}}{\rho c}\right) + \Theta_{21}\rho c + \Theta_{22}}{2 \times \exp(jkd)}\right| \quad (13)$$

where ρ is the air density, c is the speed of sound and k is the wavenumber in air.

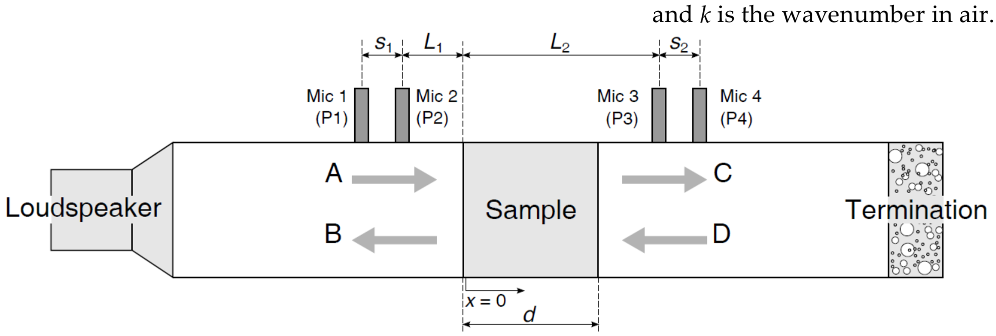

Fig. 1 – Schematic drawing of a four-microphone impedance tube

The custom-made impedance tube is made of two segments of length 1200 mm and internal diameter 45 mm. With such a cross-section, the plane-wave assumption is valid up to about 3800 Hz. The source endpoint holds a loudspeaker of 100 mm enclosed in a sealed and isolated volume, while the second endpoint is shut by a rigid reflective termination or an anechoic termination. For high-frequency measurements the microphone ports are spaced 45 mm apart, while for low-frequency measurements are spaced 500 mm. The sample is located in a separate segment of tube of appropriate length, installed between the two measurement sections described above. The model of the tube is shown in Fig. 2.

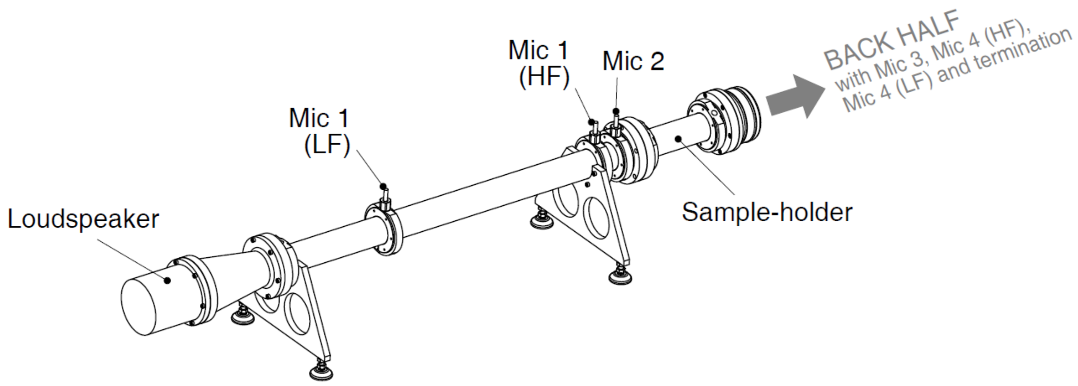

Fig. 2 – Portion of the tube including the loudspeaker. LF = low frequency; HF = high frequency

Four microphones are housed in o-ring-equipped ports and connected to a multichannel analyzer generating the test signal. A pistonphone was used to calibrate the microphones. The measured transfer functions were saved and post-processed by means of a self-built code based on the ASTM E2611 standard procedure. The script provides the acoustic parameters of the specimen, such as the sound absorption coefficient, the sound transmission loss, the propagation wavenumber, the speed of sound in the material and the characteristic acoustic impedance.

Three multilayer partitions were thermally analyzed (see Table 1). They can be considered representative of thermal coatings applied to a hollow brick wall of thickness 200 mm – P200 in Table 1 – which, alone, is characterized by poor thermal performances. The first solution, labeled P-200+WF140-80, consisted of a thermal coating of wood fiber (density 140 kg/m^3, thickness 80 mm). The second solution, labeled P-200+WF110-80+WF265-40, consisted of a thermal coating made of two layers of wood fiber (respectively density 110 kg/m^3, thickness 80 mm and density 265 kg/m^3, thickness 40 mm). The third solution, labeled P-200+A-50, consisted of a thermal coating of aerogel (density 180 kg/m^3, thickness 50 mm). All three solutions need only a layer of external plaster to be completed.

Table 1 – Thermal transmittance and periodic thermal transmittance of the analyzed multilayer partitions

Test case	Layers	λ [W/mK]	ρ [kg/m^3]	c [J/kg·K]	d [m]	d_{tot} [m]	U [W/m^{2}K]	Y_{ie} [W/m^{2}K]
P-200	Hollow bricks	0.252	817	840	0.200	0.200	1.038	0.643
P-200+WF140-80	Hollow bricks	0.252	817	840	0.200	0.280	0.337	0.0747
	Wood fiber	0.040	140	2100	0.080			
P-200+WF110-80 +WF265-40	Hollow bricks	0.252	817	840	0.200	0.320	0.256	0.0423
	Wood fiber	0.038	110	2100	0.080			
	Wood fiber	0.048	265	2100	0.040			
P-200+A-50	Hollow bricks	0.252	817	840	0.200	0.250	0.245	0.0554
	Aerogel	0.016	180	1030	0.050			

The aerogel panels are obtained through nanotechnological processes combining amorphous silica aerogel and high density reinforcing mineral fibers. Therefore, they can be considered metamaterials providing tunable thermal performance and easy to use. Other authors have used aerogel to obtain a compact soft acoustic metamaterial (Guild et al., 2016).

The thermal optimization was carried out first, then the acoustic properties of the thermally optimized structures were predicted through the transfer matrix method.

3. Results

The thermal performances of the three multilayer partitions are summarized in the Table 1.

All the proposed structures can significantly enhance the thermal performances, and consequently improve the comfort conditions inside the building, both in winter and in summer conditions. The transmittance values fulfil the limit values prescribed in Italy by the DM 26 June 2015 for vertical walls involved in building renovation. In particular, considering the more severe limit values valid by the year 2021, partition P-200+WF140-80 fulfils the limit value of 0.36 W/m²K for the thermal zone C and could be used in the thermal zones A, B and C, whereas the partitions P-200+WF110-80+WF265-40 and P-200+A-50 fulfil the limit value of 0.26 W/m²K for the thermal zone F and could be used in all the Italian thermal zones. Moreover, all the partitions have good values of periodic thermal transmittance, less than the limit value of 0.1 W/m²K. The partition P-200+A-50 is preferred since it makes it possible to obtain very good results with a small thickness.

Based on the thermal analysis, a 50 mm multilayer aerogel sample was tested in the impedance tube, while the hollow brick sound transmission loss data was derived from the sound transmission suites measurement. The acoustic performances of layered partitions featuring these two materials were predicted with the transfer matrix method (see for instance the results obtained for P-200+A-50 configuration in Fig. 3).

The addition of the aerogel layer slightly improved the sound insulation in the low frequency range, whereas the improvement was considerable above 2 kHz due to the multilayered nature of the aerogel package. The weighted single number sound reduction index for the considered façade increased from an initial performance R_w = 51 dB to an improved performance R_w = 52 dB.

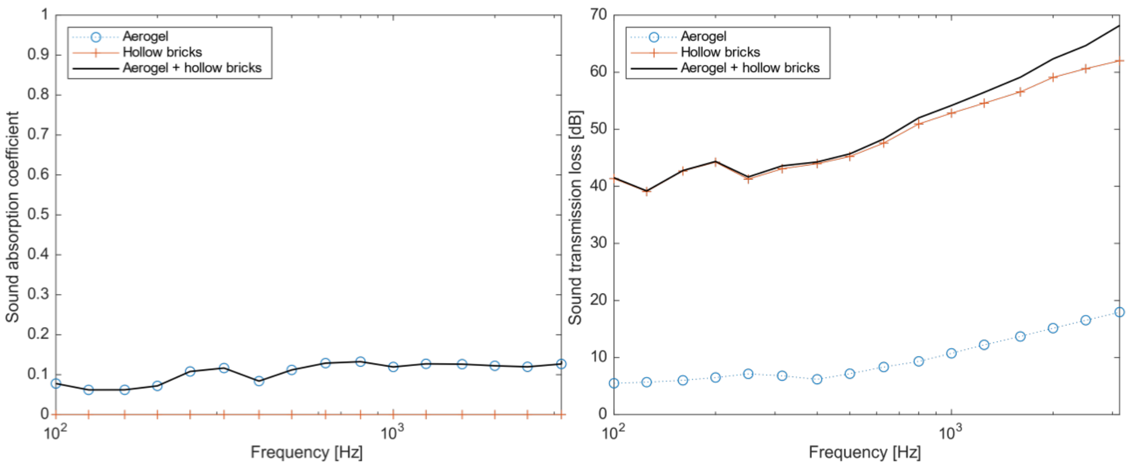

Fig. 3 – Sound absorption coefficient and sound transmission loss of aerogel and hollow brick wall (measured) and predicted properties for composite wall

4. Conclusions

In this work, the preliminary acoustic and thermal evaluation of layered structures designed for improving the performances of a façade has been proposed.

The thermal performance of different walls was simulated in accordance with ISO 13786, which

made it possible to identify the preferred structure in terms of transmittance and reduced thickness as a combination of standard hollow bricks and aerogel layers.
The acoustic analysis has been performed by the transfer matrix method with a four-microphone impedance tube, which made it possible to experimentally characterize the aerogel and to predict the behavior of the whole structure by combining the transfer matrices of the individual layers together.

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Nomenclature

Symbols

c	speed of sound (m/s)
C	thermal capacity (J/ m^{3}K)
d	thickness of the layer (m)
D_p	bending stiffness per unit width (Nm)
f	frequency (Hz)
f_c	critical frequency (Hz)
H'_T	overall heat transfer transmission coefficient (W/m^{2}K)
k	wavenumber in air (m^{-1})
M_s	surface mass (kg/m^2)
L_{ie}, L_{ei}	periodic thermal conductances (W/K)
N	layers of the multi-layer component
p	sound pressure (Pa)
R	thermal resistance (m^{2}K/W)
R_w	weighted single number sound reduction index (dB)
T	temperature (°C, K)
TL	sound transmission loss
u	particle velocity (m/s)
U	thermal transmittance (W/m^{2}K)
Y_{ee}	external thermal admittance W/m^{2}K)
Y_{ie}	periodic thermal transmittance (W/m^{2}K)
Y_{ii}	internal thermal admittance (W/m^{2}K)
$\mathbf{Z}$	heat transfer matrix (W/m^{2}K)

Greek symbols

α	sound absorption coefficient
δ	periodic penetration depth (m)
η	loss factor
λ	thermal conductivity (W/mK)
ϑ	angle of incidence
$\mathbf{\Theta}$	acoustic transfer matrix element
τ	sound transmission coefficient
ω	angular frequency (rad/s)

Subscripts/Superscripts

0	front surface
1,2,...,N	number of the layer
d	back surface
e	external
i	internal
p	panel
si	internal surface
se	external surface

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