Acoustic performance of membrane based multilayered systems with improved thermal inertia characteristics

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In this paper, the development of double membrane based systems, including phase change materials (denoted-PCM) is discussed. The cavity between the two membranes is filled with a new type of absorbing material : a 3D, nonwoven, complex structure made of two or three fibrous mats that allows the inclusion of small granulated particles while being fabricated. Granulated phase change materials are therefore included in this 3D, nonwoven structure in order to increase thermal properties by the heat storage/restoring principle. The PCMs introduced in this nonwoven structure act to store part of the heat when it is in excess, and then, to restore it when the temperature inside the room is too low. The intermediate temperature chosen to correspond to a desired comfort temperature (for example around 20°C) corresponds to the phase transition temperature of the PCM. Lightweight membranes are then fixed on each side of this complex 3D, nonwoven structure, including the PCMs. The acoustic performance of such systems is investigated in terms of the sound transmission loss, both experimentally and analytically. The thermal performance is also briefly presented.

1 Introduction

Membranes systems are already widely used as building elements such as ceilings and roofs. They are also implemented in interior spaces for acoustic reflectors or acoustic absorbers. However, different other applications such as a lightweight type tent to cover construction site or lightweight noise barrier can be developed with lightweight membrane based multi-layered systems and have been introduced in [1]. Acoustic properties of double-leaf membranes have been studied both analytically and experimentally [1, 2].

In the building sector, it has appeared quite important and interesting to develop lightweight and easy to handle double leaf composite systems combining sound insulation performance and thermal inertia improvement. Furthermore, an insulating hollow structure allowing the introduction of cables, pipes or others elements of interest such as granulated particles could provide a benefit for such double leaf systems. Granulated phase change materials (PCMs) could therefore be included in this 3D nonwoven textile fabric in order to increase thermal inertia properties by the heat storage/restoring principle. PCMs are solid at room temperature. When the temperature becomes warmer, they liquefy and absorb and store heat, thus cooling the room space (house, office, etc…). Conversely, when the temperature drops, the material will solidify and give off heat, warming the room space. By incorporating PCMs in the building envelope, they absorb the higher exterior temperature during the day, and dissipate the heat to the interior at night when it is cooler. The PCM phase transition temperature has to coincide with an intermediate temperature chosen to correspond to a desired comfort temperature (for example around 20°C). The use of PCMs has been until recently mostly in the domain of specialized sportswear; however, new applications in the building sector have been considered: they have been incorporated for example in wallboards [3].

In this paper, the development of double membrane based systems, including PCMs embedded in a 3D nonwoven textile is discussed. The PCMs are introduced in the 3D nonwoven textile during the fabrication of this complex material. Membranes are then mounted on each side of this new type 3D nonwoven textile used as a cavity absorbing element in the double leaf system as well as supporting element for the granulated PCMs. The acoustic performance of such systems is investigated in terms of the sound transmission loss, both experimentally and analytically. The thermal performance is also briefly presented

2 System description

In this section, the phase change materials are first briefly introduced. Then, the 3D non woven material used to directly incorporate the PCMs is presented. Finally, the double membrane system considered in this work is discussed.

2.1 Phase change material

A phase change material (PCM) is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. The only phase change used for PCMs is the solid-liquid change. Initially, the solid-liquid PCMs perform like conventional storage materials; their temperature rises as they absorb heat. Unlike conventional storage materials, however, when PCMs reach the temperature at which they change phase (their melting temperature) they absorb large amounts of heat without a significant rise in temperature. When the ambient temperature around a liquid material falls, the PCM solidifies, releasing its stored latent heat. Within the human comfort range of 20° to 30°C, some PCMs are very effective. They store 5 to 14 times more heat per unit volume than conventional storage materials such as water, masonry, or rock.

PCMs, currently under research and development, can smooth daily fluctuations in room temperature by lowering the peak temperatures resulting from extreme external daily temperature changes. In a typical home, they can reduce heating or cooling loads, thereby producing energy savings for the consumer, and ultimately reducing the need for new utility power plants. Initial studies have shown house heating and cooling energy savings of about 20% for PCM wallboard. Other studies showed air conditioning savings of 40% [4]. PCM insulation is most effective in climates that have large variations between day and night temperatures. This technology should also result in reductions of peak-hour energy use. It is also expected that PCMs incorporated in home elements will act as comfort enhancers.

In this work, paraffin based PCMs in the form of granulated particles were chosen since it was easy to incorporate these particles in the 3D non woven structure; their phase change is around 25-27°C. The first PCM type considered corresponds to rather large granulated particles (size between 1 and 5 mm). The second PCM type considered is in a powder form (5µm microcapsules).

2.2 3D non-woven material

In the nonwoven textile sector, the NAPCO technology is a quite innovative process to realize 3D nonwoven structures made of two or three fibrous mats. In order to interconnect the different fibrous mats by fibbers links, the machine includes a needle punching operation. It uses two needle boards working simultaneously in crossing penetration of needles through the selected fibrous mats to compose the 3D NAPCO structure. The fibbers links are created by the needles from the cut fibbers already present in the nonwoven fabric. The machine adjustments allow controlling precisely the structure thickness from 3 mm up to 50 mm, and the density of the 3D linking fibbers as well as their pattern. During the fabrication process, it is possible to insert, while the 3D NAPCO structure is being created, diverse elements such as powders, nonwoven, fibrous or foam components, cables, etc… Fig. 1 presents examples of such structures. The obtained 3D nonwoven systems are quite flexible. A finishing process such as molding, pressing, calendering can also be applied according to the final use of the 3D NAPCO material.

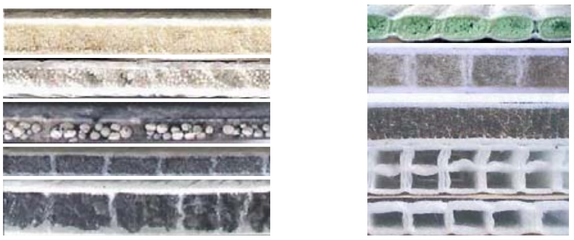

Fig.1 Examples of 3D NAPCO structures.

2.3 Double membrane system

Lightweight membrane based multi-layered systems have been previously proposed for the reduction of noise associated to road work, transportation in urban area in the form of light mobile noise barrier or tent type structure to protect frontage resident [1]. It was assumed that sound insulation in order of 15-20 dB could constitute an acceptable compromise between the system handling easiness and the acoustic performance. In [1], a prediction model based on a wave approach (infinite system) describing the vibrational response and transmitted acoustic field for a multilayered system consisting of one or two membranes with an absorbing cavity was presented. A parametric study was performed in order to investigate the influence of the membrane surface density and the cavity depth on both the transmission loss and the absorption coefficient. Experimental measurements were performed on different multilayered systems such as single and double membranes, in order to validate the analytical approach.

This previous work is extended in this paper in order to develop a lightweight membrane based double leaf system with acoustic and thermal inertia performance. The presented predicted results in terms of sound transmission have been obtained based on the model developed in [2].

For the double leaf systems evaluated in this work, the membranes are simply taped on each side of the 3D nonwoven fabric including or not PCMs; however, in the future, they could be directly fixed by coating.

Different double leaf systems are considered in this work; they correspond to different thicknesses of the 3D nonwoven fabric, different type of PCMs and different membranes in terms of their density per unit area.

3 Results

In this section, results obtained from measurements as well as from predictions for the different double leaf systems considered are presented.

The determination of the sound transmission index is based on the ISO 15186-2: the intensity approach is used to evaluate the transmitted acoustic intensity (outside the source room) while the incident intensity is deduced from the average sound pressure level in the source room.

3.1 System with large granulated PCMs

The first system considered in based on a 3D NAPCO structure composed of three nonwoven mats (one glass fibers based, a second basalt based and a third polyester based) for a total thickness of 25 mm and a density par unit area of 0.7 kg/m^2. Large granulated PCMs particles are included or not in the 3D NAPCO structure with a density par unit area of 1.9 kg/m^2 (corresponding to about 665 g/m^2 of actual PCMs). Fig. 2 shows a view of the 3D NAPCO structure realized for this first system.

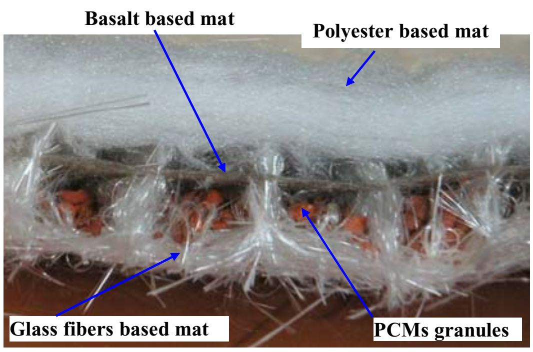

Fig.2 3D NAPCO structure with large granulated PCMs.

Due to the quantity of PCMs available for these tests, only a small sample 25x40 cm^2 was evaluated for the acoustic performance. A membrane corresponding to 1.2 kg/m^2 was placed on each side of the 3D NAPCO structure. The sound transmission index is presented in Fig. 3. First, it can be observed that the presence of PCMs has little effect on the sound transmission index of the tested system. The measured sound transmission index is quite important in the low frequency range due to the evaluated sample size; it is limited above the third octave band 1250 Hz probably due to peripheral structural flanking path. The predicted sound transmission is shown for a system size of 4x2.5 m^2: as expected is it lower than that measured in the low frequency range, and higher in the high frequency range (since flanking paths are not taken into account). However, the cavity resonance frequency in the prediction around

400 Hz is close to the one observed on the measurements (around 400-500 Hz). For the prediction, a fibrous material with properties close to those of lightweight glass wool is considered.

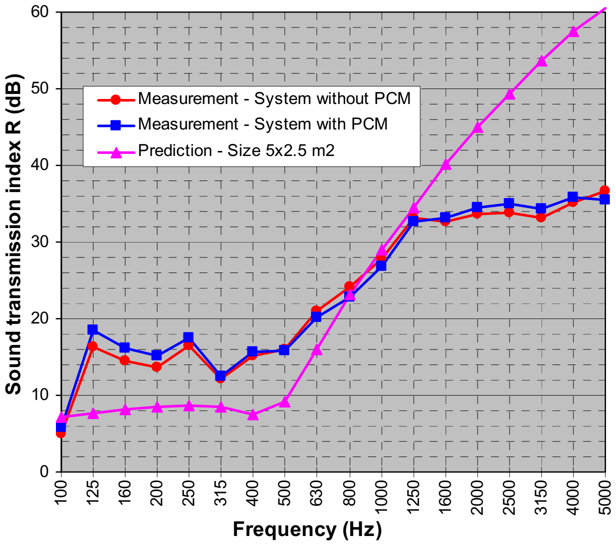

Fig.3 Sound transmission index for system with large granulated PCMs.

Measurements have shown that thermal resistance is not modified by the presence of the large granulated PCMs particles in the 3D NAPCO nonwoven structure.

Thermal inertia associated to the presence of PCMs in a system is evaluated by measuring enthalpy. This method allows determining the system thermal storage capacity within a temperature range using a heatflowmeter (i.e., thermal conductivity measurement equipment). For a temperature frequency range of 15-30°C, results show that the system including PCMs can store 165 kJ/m² while the system without PCM only 50 kJ/m². Therefore, the presence of PCMs in the system increases the thermal capacity by 300%. For example, plasterboard 12.5mm in thickness, under the same condition would store 195 kJ/m². Therefore, the system with PCMs considered in this work is associated to heat storage par unit mass 3 times larger than the plasterboard.

Another method consists in measuring the heat flow and the temperature on each side a tested element under variable temperature conditions. On one side of the tested element an air cavity is temperature regulated (either with sinusoidal or ramp variation); and on the other side, a thermal insulating layer maintains a zero heat flow. Fig. 4 presents the system behaviour under a sinusoidal temperature variation. It can be noticed that the presence of the PCM provides one hour delay in reaching the temperature maximum. The thermal damping (lowering of maximum temperature) is more related to the thermal resistance of the 3D nonwoven fabric than the presence of PCM: the maximum temperature reached under the sinusoidal temperature variation is close for systems with and without PCM. However, the comparison with the plasterboard shows a thermal damping gain in the order of 2°C.

3.2 Systems without PCM

Since the effect of the PCMs presence in the 3D NAPCO structure was found negligible on the sound transmission index, more acoustic performance measurements were carried out without PCMs in double leaf systems. Two different 3D NAPCO structures were fabricated. The first one is 20 mm thick and composed of two identical nonwoven glass fibers mats. The second one is 30 mm thick and consists of three similar mats (the intermediate one being slightly off center). Fig. 5 presents a view of these two nonwoven structures.

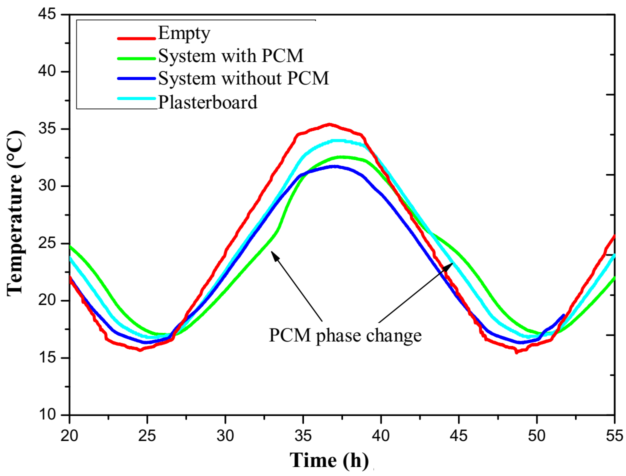

Fig.4 Thermal behavior under sinusoidal temperature variation for system with large granulated PCMs.

The evaluation of the sound transmission index was carried out on an element of size 2x1 m^2. A membrane corresponding to 1.2 kg/m^2 was placed on each side of the two 3D NAPCO structures described above. Both systems are associated to a density per unit mass below 5 kg/m^2. The sound transmission index is presented in Fig. 6.

Fig.5 3D NAPCO structures without PCM; (a) two mat and (b) three mat structures.

First, it should be noticed that measurements are in good agreement with the predictions. For the predictions, a fibrous material with properties close to those of lightweight glass wool is again considered. The acoustic performance for both tested systems is quite similar. The cavity resonance frequency is lower for the system with the 30 mm thick 3D NAPCO structure (3 mat structure) than for the 20 mm thick one (2 mat structure); it is decreased from the third octave 400 Hz to 315 Hz. However, the sound transmission index for the third octave band corresponding to this cavity resonance frequency is lower for the 30 mm thick 3D NAPCO structure (3 mat structure) than for the 20 mm thick one (2 mat structure). Therefore, as seen in Table 1, the acoustic performance global index Rw+C obtained from the measurement is decreased by 1 dB when the 30 mm thick 3D NAPCO structure is used rather than the 20 mm thick one.

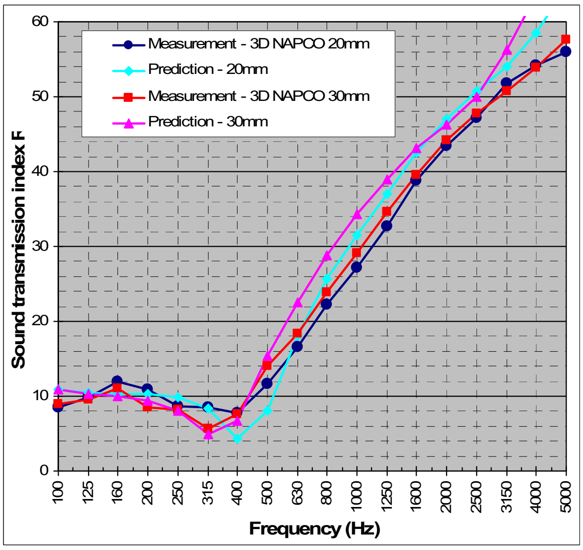

Fig.6 Sound transmission index for systems without PCM.

System				
R dB(A)	Rw dB	C dB	Rw+C dB	Ctr dB
Prediction – Single leaf 1.2 kg/m^2				
15	14	0	14	-3
Measurement – Double leaf 1.2 kg/m^2 – 20 mm 3D NAPCO – 1.2 kg/m^2				
19	19	-1	18	-4
Prediction – Double leaf 1.2 kg/m^2 – 20 mm – 1.2 kg/m^2				
17	18	-2	16	-5
Measurement – Double leaf 1.2 kg/m^2 – 30 mm 3D NAPCO – 1.2 kg/m^2				
18	19	-2	17	-5
Prediction – Double leaf 1.2 kg/m^2 – 30 mm – 1.2 kg/m^2				
18	19	-2	17	-5

Table 1 Global acoustic index for systems without PCM

Therefore, it is possible to obtain a lightweight system (less than 5 kg/m^2) with quite acceptable acoustic performance. The behavior associated to the 3D NAPCO structure in the cavity is very similar to the one of a lightweight glass wool layer. The advantage of using a 3D NAPCO structure is that extra elements (such as PCMs, ...) can be easily included during its fabrication.

3.3 Thin Systems with micro-PCMs

In order to be able to carry out an automatic continuous lamination of the membranes, the thickness of the intermediate component (forming the cavity in the double leaf system) should be limited to a maximum of 10 mm. It was thus decided to evaluate a thin double leaf system with a thickness limited to 5 mm. This order of thickness also allows the double leaf system to be easily rolled for storage at the end of a production line. Therefore, a thin 3D NAPCO structure was developed. To include PCMs in such a thin 3D nonwoven structure, a powder made of microencapsulated PCMs was selected. A light membrane of 0.6 kg/m^2 is then applied on each side of the 3D NAPCO structure including or not the micro-PCMs. The double leaf systems obtained in this case are about 5 mm thick and a maximum density per unit area of 2 kg/m^2 (obtained for the system including the micro-PCMs). The density per unit area of PCMs is about 250 g/m^2. A double leaf system with a thin standard silicone foam (2-3 mm thick) as intermediate component was also considered. Fig. 7 presents the sound transmission index measured for the different configurations considered.

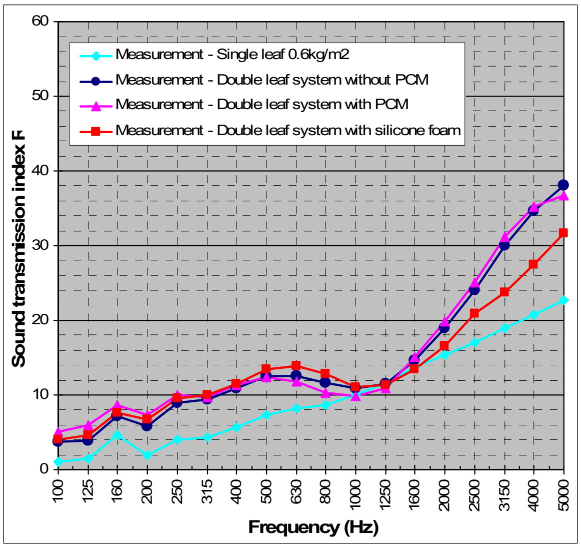

Fig.7 Sound transmission index for thin systems with or without micro-PCMs.

The acoustic results obtained for these thin systems are as expected lower than those previously achieved (presented in previous sections). This lower performance is due to the lower membrane density par unit area used for these thin systems, as well as the lower thickness of the intermediate component between the two leafs (i.e. cavity thickness). The cavity resonance frequency associated to double leaf behaviour is placed above 1000 Hz rather than around 400 Hz for the thicker systems tested before. The three double leaf systems evaluated are associated with a similar acoustic performance: their global acoustic index R_w+C is 13 dB as seen in Table 2. This acoustic performance level is still quite interesting related to the total thickness and the density par unit area of these systems. As observed before, the presence of the micro-PCMs in the 3D NAPCO structure does not very much affect the acoustic behaviour of the double system.

System				
R dB(A)	Rw dB	C dB	Rw+C dB	Ctr dB
Single leaf 0.6 kg/m^2				
11	11	-1	10	-3
Double leaf – 3D NAPCO without micro-PCMs				
14	14	-1	13	-3
Double leaf – 3D NAPCO with micro-PCMs				
14	14	-1	13	-3
Double leaf – Silicone foam				
14	14	-1	13	-2

Table 2 Global acoustic index from measurements on thin systems with or without micro-PCMs

Thermal conductivity is not largely modified by the presence of the micro-PCMs in the 3D NAPCO nonwoven structure. However, it is much larger for the silicone foam considered. Thermal inertia associated to the presence of micro-PCMs in this thin system was evaluated using the methods discussed previously. For a temperature frequency range of 15-30°C, results show that the thin system including micro-PCMs can store 107 kJ/m² while the system without micro-PCM around 69 kJ/m². Therefore, the presence of PCM in the system increases the thermal capacity only by 50%. It is much lower than the results obtained with the large granulated PCMs particles (thermal capacity increased by 300%). This is mainly related to the difference in density par unit area of PCMs included in the 3D NAPCO structure (250g/m² for micro-PCMs and 665 g/m² for the large granular PCMs). The thermal capacity per m^2 measured for the system with the silicone foam is similar that that of the 3D NAPCO system without micro-PCM. The behaviour of the system with and without micro-PCMs in the 3D NAPCO structure, under variable temperature conditions is quite similar: the amount of micro-PCMs included in the 3D NAPCO structure is too limited to be associated to noticeable effect.

5 Conclusion

Measurements have shown that thermal conductivity is not modified by the presence of PCMs in the 3D NAPCO nonwoven structure. The thermal insulation performance is therefore not changed. Concerning thermal inertia, measurements have shown that the presence of PCMs is associated to an increase in heat storage efficiency in the nonwoven textile in which they are included as long as their amount (i.e. density per unit area) is sufficient. The dynamic thermal measurements (behaviour under variable temperature conditions) have shown that the presence of PCMs in the 3D NAPCO structure can delay the extreme temperatures by approximately an hour ; the use of the 3D NAPCO structure allow a thermal damping of the temperature amplitude. From the measurements performed on the two different amounts of PCMs per m^2, it can be deduced than about 1 kg/m^2 of PCMs in the 3D NAPCO structure should be used in order to achieve quite interesting thermal properties.

Concerning the acoustic performance, measurements have shown that the presence of the PCMs has limited effect on the sound transmission index. The acoustic performance of the double leaf system is directly related to the density par unit area of the system and the thickness of the intermediate component (double leaf cavity).

The acoustic performance R_w+C is around 17-18 dB for the double leaf systems with 1.2 kg/m^2 membranes (total density par unit area lower than 5 kg/m^2) and a thick 3D NAPCO structure (20 or 30 mm in thickness). For the thin (total thickness around 5 mm) and lightweight (total density per unit area around 2 kg/m^2) double leaf systems considered, the acoustic performance R_w+C is around 13 dB.

Therefore, this work has demonstrated the feasibility to develop a textile lightweight system for building application combining acoustic and thermal performance. The classical thermal performance can be improved by the use of PCMs (in enough quantity) in order to obtain thermal inertia usually missing in standard lightweight structure.

Acknowledgments

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