THERMAL BEHAVIOUR OF MEDITERRANEAN BUILDINGS: EXPERIMENTAL STUDY

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Abstract

This work presents an experimental and theoretical study to compare the thermal behaviour of different constructive solutions. The experimental set-up consists of several house-like cubicles (with inner dimensions of 2.4x2.4x2.4 m) located in Puigverd de Lleida (Lleida, Spain). Their thermal performance throughout the time was measured and presented for two different types of experiments: free floating and fixed controlled temperature conditions. In order to control the inner temperature an electric radiator and a heat pump were used for heating and cooling, respectively, and the energy consumption was registered. This work is focused on the thermal behaviour of four cubicles: a reference cubicle without insulation, a cubicle insulated with 5 cm of polyurethane foam, a cubicle insulated with 5 cm of mineral wool, and a cubicle with a constructive solution based on alveolar bricks without insulation. The thermal transmittance in steady state, also known as U-value, is theoretically calculated for each cubicle. Dynamic thermal characteristics, such as decrement factor, thermal lag, and dynamic thermal transmittance are also evaluated using the heat transfer matrix to analyze the thermal inertia. The experimental results extracted from the monitored cubicles show that the energy consumption for the insulated cubicles and the alveolar brick one is similar, achieving a reduction in comparison to the reference cubicle of about 38% and 45% during summer and winter, respectively.

1. Introduction

It is well known that during the last years, the energy demand for cooling and heating has increased significantly in the building sector. In order to improve the thermal behaviour in buildings, insulating materials have been widely used [1] as well as different constructive solutions based on Alveolar brick [2]. Alveolar brick provides thermal insulation by itself with no necessity of additional insulation.

The use of insulation materials like polyurethane, mineral wool and a more simple constructive solution based on alveolar bricks is experimentally discussed in this paper.

Besides, the thermal transmittance in steady state (know also as U-value) of these different constructive solutions is calculated theoretically. The U-value is the parameter which has to be taken into consideration when designing the insulation in buildings according to the Spanish building code [3].

Furthermore, not only the U-Value is calculated, but other dynamic thermal characteristics as well such as decrement factor, thermal lag, and dynamic thermal transmittance as they can have a clear effect on the energy consumption and consequently, on the choice of the appropriate insulation material and method as well ([10] and [11]). Using the heat transfer matrix method described on pipes

[4] and on ISO 13786 [5] these dynamic thermal characteristics (decrement factor, thermal lag and dynamic thermal transmittance) are calculated as it is developed on Hall [6].

2. Experimental setup

The experimental set-up studied in this paper consists of four real cubicles located in Puigverd de Lleida (Lleida, Spain) (Figure 1). The cubicles have the same inner dimensions (2.4x2.4x2.4m) but with different constructive solutions. Three of them present typical Mediterranean construction based on (from inside to outside): perforated bricks, insulation, air chamber and hollow bricks. One of these three has no insulation; the other two are insulated with 5 cm of polyurethane and 5 cm of mineral wool, respectively. The fourth cubicle has no insulation and its constructive solution is based on alveolar bricks. Figure 2, Figure 3, and Figure 4 show a section of the constructive solution for the studied cubicles.

Fig1. Demonstration cubicles in Puigverd de Lleida.

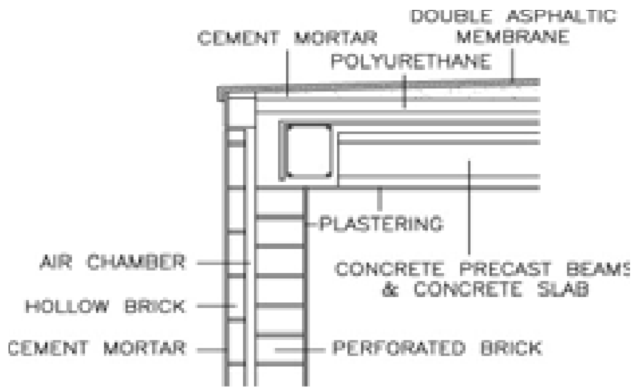

Fig 2. Section of the constructive solution for the reference cubicle

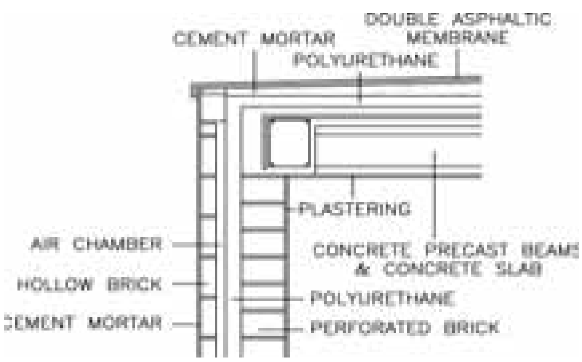

Fig 3. Section of the constructive solution for the insulated cubicles

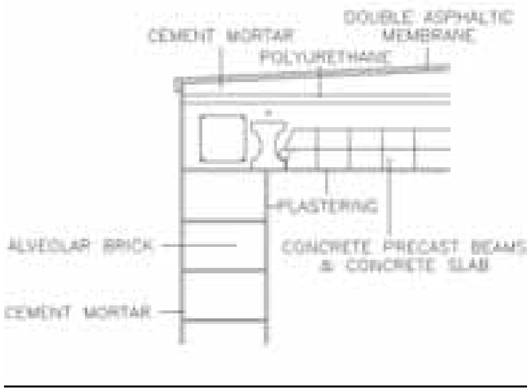

Fig 4. Section of the constructive solution for the Alveolar cubicle.

Two kinds of experiments have been carried out: free floating temperature and fixed controlled temperature. Electrical radiators and heat pumps are used to control the temperature set point during winter and summer, respectively.

For a suitable representative study, the week chosen to be studied in this paper is from the period of July 22, 2008 until July 30, 2008. Temperatures are typical for summer time in continental-Mediterranean weather, that is, mild at nights and hot during the day, oscillating from 15 to 35 ºC, as shown in Figure 5. Outside temperature patterns are very similar during the week, being the first and the last day a little less hot than the rest of the week days, and the solar radiation peaks are between 850 and 950 W/m^2 every day.

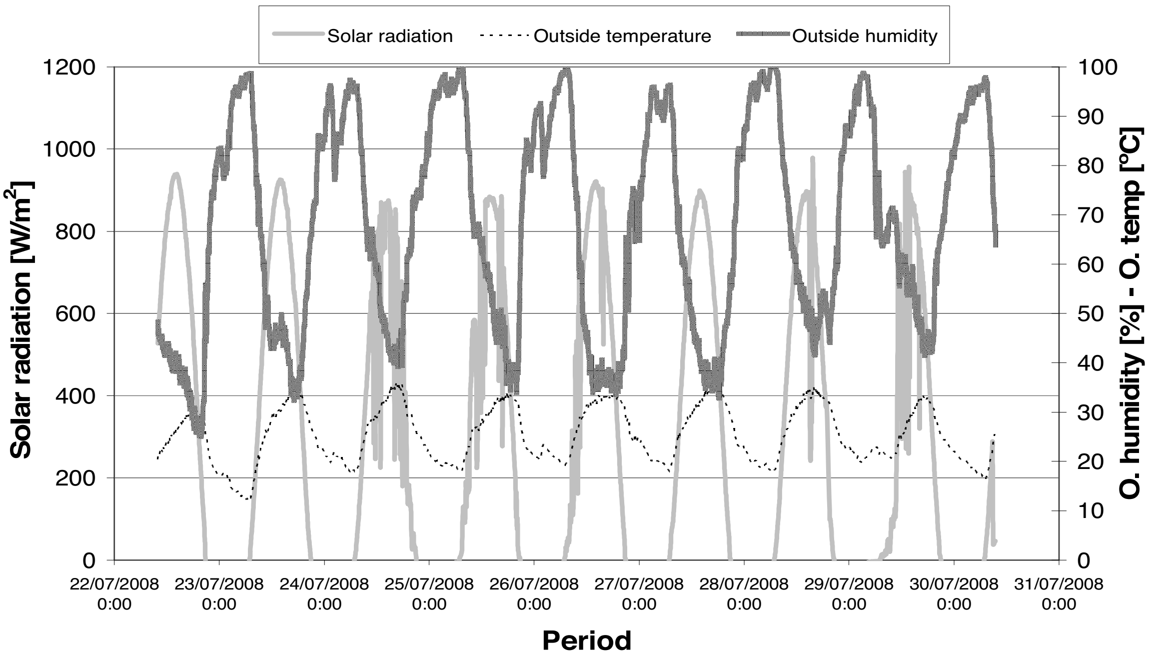

Fig 5. Weather data for the considered week: solar radiation, outside temperature, and outside humidity.

3. Theoretical Methodology

3.1 Thermal Transmittance in Steady-State (U-value)

The thermal transmittance in steady-state (U-value) is given as the inverse of the total thermal resistance of a composite wall, sum of the thermal resistances of each layer in the wall.

For each layer, both thickness and thermal conductivity are known, as well as the inner and outer convective heat transfer coefficients which are assumed to be 7.69 and 25 W/m^2·K, respectively, as it is detailed in [7].

$$U = \frac{1}{\frac{1}{h_{ext}} + \sum_{i=1}^{n} \frac{d_i}{\lambda_i} + \frac{1}{h_{int}}} \quad (1)$$

3.2 Dynamic thermal characteristics

Using the heat transfer matrix method described in [4] while assuming constant thermal properties of a homogeneous and isotropic layer and one-dimensional heat flux, the heat transfer equation in a solid layer of a building component is given by:

$$\frac{\partial T(x,t)}{\partial t} = \frac{\lambda}{\rho C_p} \frac{\partial^2 T(x,t)}{\partial x^2} \quad (2)$$

And the heat flow per unity of surface through the wall is given by:

$$q(x,t) = -\lambda \frac{\partial T(x,t)}{\partial x} \quad (3)$$

In terms of Laplace variables [8], the matrix that defines the relation between the temperature and the heat flux at both sides of the m layer is given by:

$$\begin{pmatrix} \hat{T}_{ext} \\ \hat{q}_{ext} \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \cdot \begin{pmatrix} \hat{T}_{int} \\ \hat{q}_{int} \end{pmatrix} \quad (4)$$

The matrix coefficients for each layer can be calculated by:

$$m_{11} = m_{22} = \cosh\left(d \sqrt{\frac{sC_p \rho}{\lambda}} \right) \quad (5)$$

$$m_{12} = \frac{\sinh\left(d \sqrt{\frac{sC_p \rho}{\lambda}} \right)}{\lambda \sqrt{\frac{sC_p \rho}{\lambda}}} \quad (6)$$

$$m_{21} = \lambda\sqrt{\frac{sC_p\rho}{\lambda}}\sinh\left(d\sqrt{\frac{sC_p\rho}{\lambda}}\right) \quad (7)$$

The matrix coefficients for an air chamber or a surface resistance between the layer and the environment are:

$$m_{11} = m_{22} = 1 \quad (8)$$

$$m_{12} = -R_a \quad (9)$$

$$m_{21} = 0 \quad (10)$$

Finally for a multi-layered wall, the overall operational transmission matrix Z is given by the products of the individual transmission matrices of the separate slabs:

$$\begin{pmatrix}\hat{T}_{ext}\\ \hat{q}_{ext}\end{pmatrix} = \begin{pmatrix}1 & -R_{a,ext}\\ 0 & 1\end{pmatrix}\begin{pmatrix}m_{11} & m_{12}\\ m_{21} & m_{22}\end{pmatrix}\begin{pmatrix}n_{11} & n_{12}\\ n_{21} & n_{22}\end{pmatrix}\cdots\begin{pmatrix}1 & -R_{a,\mathrm{int}}\\ 0 & 1\end{pmatrix}\begin{pmatrix}\hat{T}_{int}\\ \hat{q}_{int}\end{pmatrix} \quad (11)$$

$$\begin{pmatrix}\hat{T}_{ext}\\ \hat{q}_{ext}\end{pmatrix} = \begin{pmatrix}Z_{11} & Z_{12}\\ Z_{21} & Z_{22}\end{pmatrix}\begin{pmatrix}\hat{T}_{int}\\ \hat{q}_{int}\end{pmatrix} \quad (12)$$

By substituting the Laplace variables in the total transfer matrix Z for j·ω ($j = \sqrt{-1}$) as it is described in [5] and [6], the decrement factor (f), the thermal lag (ϕ), and the dynamic thermal transmittance (Y_{12}) can be calculated as:

$$f = \frac{1}{|Z_{12}|U} \quad (13)$$

$$\phi = \frac{12}{\pi}\arctan\left(\frac{\mathrm{Im}(-Z_{12})}{\mathrm{Re}(-Z_{12})}\right) \quad (14)$$

$$|Y_{12}| = f \cdot U = \frac{1}{|Z_{12}|} \quad (15)$$

Where the thermal lag is the time it takes for a heat wave to propagate from the outer surface to the inner surface and the decreasing ratio of its amplitude during this process is named as decrement factor [10]. The thermal transmittance represents the ratio between the complex amplitude of the heat flow rate through the surface adjacent to zone 1 (inner), and the complex amplitude of the temperature in zone 2 (outer).

4. Results and discussion

Figure 6 shows the measurements of the electrical heat pump consumption during the specified week. It can be noticed that the insulated cubicles and the alveolar brick cubicle achieved energy savings in comparison to the reference cubicle of about 38% and 45%, respectively.

For each of the studied cubicles, the results of the analysis of the steady state thermal transmittance (U-Value), and results of the analysis of the dynamic thermal characteristics which are evaluated using the heat transfer matrix method described on [4] and [5] are shown in Table 1.These dynamic thermal characteristics are presented with the following three parameters: decrement factor (f), the thermal lag (ϕ), and the dynamic thermal transmittance (Y_{12}).

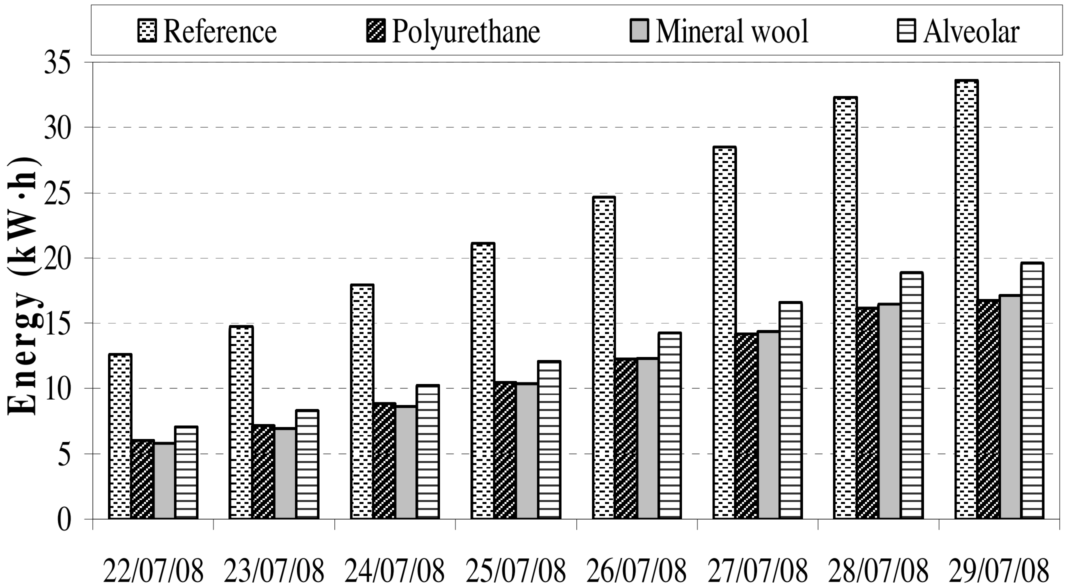

Fig 6. Accumulated energy consumption during the considered week of July 2008 for each cubicle.

Although the Alveolar cubicle has no insulation and has higher U-Value (Table1), there is no significant difference in the energy consumption levels between the alveolar cubicle and the insulated ones (Figure 6).

This fact is due to the effect of the high thermal inertia of the alveolar bricks which is analyzed by the dynamic thermal characteristics of the cubicles that are presented in Table 1. These factors are the decrement factor (f), and the time lag (ϕ) and the dynamic thermal transmittance (Y_{12}). The results obtained are consistent with the energy consumption differences observed in the experiments and can justify the thermal behaviour of these different constructive solutions.

Table 1. U-value and dynamic thermal characteristics results for each cubicle.

Parameter	Reference	Polyurethane	Mineral Wool	Alveolar
U-value [W/m^{2}K]	1.21	0.38	0.50	0.78
Decrement factor	0.51	0.38	0.34	0.19
Time lag [h]	6.87	8.32	8.56	12.55
Dynamic Thermal Transmittance (W/m2·K)	0.623	0.15	0.17	0.15

5. Conclusions

Experimental and theoretical studies have been carried out to compare the thermal behaviour of different constructive solutions of four experimental cubicles: a reference cubicle without insulation, a cubicle insulated with 5 cm of polyurethane foam, a cubicle insulated with 5 cm of mineral wool and a cubicle with a constructive solution based on alveolar bricks without insulation

In the experimental part, the energy consumption for the four cubicles was registered and the results showed that although the alveolar brick cubicle has no insulation, there was no significant difference between its measured energy consumption compared to the insulated ones. However, the calculated U-value presented significant differences between the alveolar brick cubicle and the insulated ones. Therefore, one expected a bigger difference in the energy consumption.

The main reason of this disagreement is caused by the high thermal inertia of the alveolar bricks, which can be analyzed by the dynamic thermal characteristics using the heat transfer matrix method described on [4] and [5]. The results of such parameters are consistent with the energy consumption tendencies and represent in a better way the thermal behaviour of the different constructive solutions.

From this work, some recommendations can be drawn:

- According to the Spanish building code [3], only the thermal transmittance in steady state (U-Value) is considered in designing a suitable insulation for a building. However, from the results shown in this paper, it can be concluded that it is important also to consider other dynamic thermal characteristics such as the decrement factor, time lag, and dynamic thermal transmittance beside the thermal transmittance in steady state (U-Value).
- In a future work, adding insulation to the alveolar brick cubicle can further increase the energy savings achieved by this constructive solution.
- As previously studied in [10] and [11], the position and thickness of an insulation of a wall can have a profound effect on the time lag and decrement factor. The studied cubicles are insulated

internally; therefore a constructive solution using external insulation or even both internal and external insulation can be analyzed in the future.

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References

[1] L.F.Cabeza, A.Castell, M.Medrano, I.Martorell, G.Pérez, I.Fernández, Experimental study on the performance of insulation materials in Mediterranean construction, Energy and Buildings (2009) doi:10.1016/j.enbuild.2009.10.033. 28-33.

[2] A. Castell, I. Martorella, M. Medranoa, G. Péreza and L.F. Cabeza, Experimental study on the performance of insulation materials in Mediterranean construction, Energy and Buildings (2009) doi:10.1016/j.enbuild.2009.10.022 .

[3] Spanish Building Code, "CTE, Código Técnico de la Edificación", Spanish Minisitry for Dwellings, 2006.

[4] L.A.Pipes, Matrix analysis of heat transfer problems, J.Franklin Institute 623 (1957) 195-206.

[5] EN ISO 13786:2001, Thermal performance of building components, Dynamic Thermal Characteristics, Calculation Methods.

[6] M.Hall, D.Allinson, Assessing the moisture content dependent parameters of materials using the cyclic-response admittance method, Energy and Buildings 40 (2008) 2044-2051.

[7] EN ISO 6964:1996, Building components and building elements. Thermal resistance and thermal transmittance. Calculation method.

[8] H.S.Carslaw, J.C.Jaeger, Conduction of heat in solids, Oxford University Press, Oxford, ISBN: 0198533683, 1959.

[9] N.Aste, A.Angelotti, M.Buzzetti, The influence of the external walls thermal inertia on the energy performance of well insulated buildings, Energy and Buildings 41 (2009) 1198-1187.

[10] H. Asan, Effect of wall´s insulation thickness and position on time lag and decrement factor (1998), doi:10.1016/S0378-7788(98)00030-9 .

[11] H. Asan, Investigation of wall's optimum insulation position from maximum time lag and minimum decrement factor point of view (2000) ,doi:10.1016/S0378-7788(00)00044-X