Wall/Roof thermal performance differences between air-conditioned and non air-conditioned rooms

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Abstract

A one dimensional heat transfer model for periodic outdoor conditions is presented and used to evaluate the thermal performance of a monolayered and multilayered envelope wall/roof in an air-conditioned and in a non air-conditioned room. Three materials are tested for a monolayered wall/roof: high density concrete (HDC), aerated concrete (AeC), and expanded polystyrene foam (EPS). Three multilayered walls/roofs of width $0.10m$ are considered composed by a sheet of $0.02m$ of EPS and the rest of HDC. The EPS can be on the outside, middle or inside of the wall/roof. The main conclusion is that an appropriate wall/roof for an air-conditioned room may not be suitable for a non air-conditioned one. For the monolayered wall/roof and conditions under study, it is found that in an air-conditioned room the most important physical property of the wall/roof is its thermal conductivity, which has to be as small as possible, while for the non air-conditioned room the most important physical property is the thermal diffusivity, which also has to be as small as possible. In this case the position of the insulation in a multilayered wall/roof is important.

Keywords: wall/roof thermal performance, periodic outdoor conditions, air-conditioned, non air-conditioned.

1. Introduction

In general, the focus on evaluating the thermal performance of envelope building walls or roofs has been the reduction on heating and cooling energy

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consumption. In other words, the time dependent analysis of the heat transfer through a wall/roof aimed to study the effect of the materials and their relative location reported in the literature have considered that the indoor temperature is held constant by thermomechanical means. The analytical solution of the one dimensional heat transfer equation for periodic outdoor temperature through a monolayered wall, with constant material properties, with indoor and outdoor fixed surfaces film coefficients was obtained by Alford *et al.* [1] and discussed in the book by Kuehn *et al.* [2]. Mackey and Wright developed a method, based on empirical results to evaluate the temperature of the inside surface of the monolayered [3] and multilayered wall or roof [4]. These methods were discussed by Givoni [5]. The one dimensional heat transfer equation for periodic outdoor conditions through a multilayered wall was solved by Stephenson and Mitalas using the Laplace-transform [6]. This procedure is known as the transfer-function method [2]. Kusuda [7] extended this method for cylindrical, spherical and semi-infinite layers. Chen and Krokosky [8] used a finite element technique to numerically solve the two dimensional heat transfer equation for periodic outdoor conditions for mono and multilayered roofs. The finite element technique gives similar results as the one dimensional analytical solution for monolayered roofs. They compared numerical results with experimental results, demonstrating that the finite element technique gives better results than the Mackey and Wright method for multilayered roofs. The effect on the wall/roof thermal performance, for periodic outdoor conditions, of the layered materials and their relative location was theoretically [9], numerically [10, 11, 12, 13, 14], and experimentally evaluated [11, 15].

The aim of this work is to compare the thermal performance of a wall/roof in air-conditioned (constant indoor temperature) and in non air-conditioned (free floating indoor temperature) rooms.

In general, the proportional area of a wall or roof where the end-effects are important is not significant. This suggests that a one dimensional model of a roof or wall, that by its construction disregards end-effects, is a good approximation for thermal evaluation. In places with large daily temperature variations or important solar radiation variations a time dependent heat transfer analysis is needed. Thus in this work, the one dimensional heat transfer equation for periodic outdoor conditions is used to evaluate the thermal performance of a monolayered or multilayered wall/roof. This equation is numerically solved using an explicit volume finite scheme considering constant material properties and outdoor and indoor film heat transfer coefficients.

2. Model

The one dimensional heat transfer equation through a wall or roof composed by N layers of a total lenght L is [16]

$$\frac{\partial T}{\partial t} = \alpha_j \frac{\partial^2 T}{\partial x^2}, \tag{1}$$

where α_j is the thermal diffusivity of the j-th material layer, T the temperature, t the time, and x the position.

The following condition must be satisfied in all unions between layers,

$$k_j \left.\frac{dT}{dx}\right|_{j,j+1} = k_{j+1} \left.\frac{dT}{dx}\right|_{j,j+1}, \tag{2}$$

where k_j and k_{j+1} are the thermal conductivities of the j-th and $(j+1)$-th layers, respectively, and $j, j+1$ denotes that the derivative is evaluated in the interface of the j-th and $(j+1)$-th layers.

In order to solve the equation, the boundary conditions on both sides of the wall/roof are needed. The outdoor boundary condition is

$$-k_1 \left.\frac{\partial T}{\partial x}\right|_{x=0} = h_{out}(T_{sa} - T_{x=0}), \tag{3}$$

where h_{out} and $T_{x=0}$ are the film heat transfer coefficient and the temperature on the outdoor surface, respectively. The sol-air temperature T_{sa} of the previous Eq. is defined by [17]

$$T_{sa}(t) = T_a(t) + I(t)\frac{\alpha}{h_{out}} - RF, \tag{4}$$

where $T_a(t)$ is the instantaneous temperature of the outdoor air, $I(t)$ is the instantaneous solar radiation, α the absorptivity of the outdoor surface, and, RF is the infrared radiation factor. Given the maximum and minimum of T_a and the times of day when they occur, $T_a(t)$ was calculated for one day with the model proposed by Chow and Levermore [18]. The indoor boundary condition is

$$-k_N \left.\frac{\partial T}{\partial x}\right|_{x=L} = h_{in}(T_{in} - T_{x=L}), \tag{5}$$

where h_{in} and $T_{x=L}$ are the film heat transfer coefficient and temperature on the indoor surface, respectively, and T_{in} is the indoor air temperature.

Three cases are considered, a room with air-conditioning (A/C), a room with no air-conditioning(nA/C), and the transient state in a room when the air-conditioning is turn on(A/C-on) at a certain hour. In the first case, T_{in} in Eq. (5) is considered constant and known. For the nA/C case, T_{in} is calculated using

$$d\rho_a c_a \left(\frac{dT_{in}}{dt}\right) = h_{in}(T_{in} - T_{x=L}), \tag{6}$$

where ρ_a and c_a are the density and specific heat of air and d is the distance to a place where an adiabatic or symmetry condition can be assumed, $(d \gg L)$. This equation relates the temporal change in thermal energy of the air inside the room, where perfect mixing is assumed, and the heat transfer through the wall/roof. For the third case, T_{in} was calculated as in nA/C case until periodic temperature is obtained, then at a given time the air-conditioning is turned on. From the turn on time the equation for the temporal change in thermal energy of the air inside the room has to consider both the heat transfer through the wall/roof and the heat transfer due to the difference in energy between the exiting air at temperature T_{in} and the incoming air from the air-conditioning plant at a fixed temperature $T_{A/C}$. Assuming perfect air mixing this equation is

$$d\rho_a c_a \left(\frac{dT_{in}}{dt}\right) = h_{in}(T_{in} - T_{x=L}) + Cd\rho_a c_a(T_{A/C} - T_{in}), \tag{7}$$

where C is the number of air changes in a room per unit of time.

The heat transfer in the bulk of any wall/roof layer is governed by its thermal diffusivity (Eq. (1)), while for the heat transfer through layers (Eq. (2)) and through outdoor and indoor boundaries (Eqs. (3) and (5)), the thermal property of the layers involved is the thermal conductivity. The heat transfer through the outdoor and indoor boundaries is also governed by the corresponding film heat transfer coefficient, but for evaluating different wall/roof in the same conditions, their values are fixed.

Eq. (1) with the corresponding boundary conditions is solved using an explicit volume finite scheme [19]. For the A/C and nA/C cases, an iterative procedure is used during a time tr in order to reach a periodic condition for which $|T(x, t_r) - T(x, t_r + 24)| < 0.1$ for all x, where T is in degrees Celsius and t_r is in hours.

The code was validated with an analytical solution of a one dimensional layer initially at a uniform temperature. For $t > 0$ the temperature of one boundary changes to a different constant value and the other boundary is adiabatic [19].

In the A/C case the important parameter to analyze the thermal performance of the wall/roof is the daily energy per unit area E needed to keep the room at the comfort temperature T_c. This temperature is calculated by [20]

$$T_c = 13.5°C + 0.54T_{am}, \tag{8}$$

where T_{am} is the daily mean temperature of the outdoor air, in $°C$.

For the nA/C case the important parameters are the decrement factor DF and the lag time LT. The decrement factor is calculated by

$$DF = \frac{T_{in_{max}} - T_{in_{min}}}{T_{sa_{max}} - T_{sa_{min}}}, \tag{9}$$

where $T_{in_{max}}$ and $T_{in_{min}}$ are the maximum and minimum indoor air temperatures, respectively, $T_{sa_{max}}$ and $T_{sa_{min}}$ are the maximum and minimum sol-air temperatures, respectively. The lag time is defined as

$$LT = t(T_{in_{max}}) - t(T_{sa_{max}}), \tag{10}$$

where $t(T_{in_{max}})$ and $t(T_{sa_{max}})$ are the time of the day when the indoor air and sol-air temperatures reach their maxima, respectively.

It is desirable that DF be small and that LT be large. In practical situations the LT value does not exceed twelve hours. When $DF \lesssim 0.1$ the value of LT is not important.

For the A/C-on case, the important parameter is the elapsed time Δt_c from the turn on time to the moment when the indoor air temperature achieves the comfort temperature T_c. A wall/roof configuration is better if Δt_c is smaller.

3. Numerical simulations

All numerical simulations were carried out considering a horizontal roof, so $RF = 3.9°C$ [17] and the solar radiation is approximated by a sinusoidal with its maximum (900 W/m^2) at the solar mid-day, sunrise at 6:00 hours, and the sunset at 18:00 hours. The minimum and maximum temperatures are $T_{min} = 20°C$ and $T_{max} = 35°C$, which occur at the sunrise and two hours later of the solar mid-day, respectively. The outside and inside film heat transfer coefficients are $h_{out} = 13W/m^2\,°C$ and $h_{in} = 6.6W/m^2\,°C$, respectively. The roof exterior surface absorptivity is $\alpha = 0.4$ (gray color) [5] and the distance to the adiabatic point is $d = 2.5m$ (height of the room).

Six roof configurations were considered in both the A/C and the nA/C cases. Three are monolayered roofs made of high density concrete (HDC), aerated concrete (AeC), and expanded polystyrene foam (EPS). The other three are multilayered roofs made of $0.08m$ of HDC and $0.02m$ of EPS placed in the following ways. The EPS is in contact with the exterior (EPS$_{ext}$), the EPS is in the middle of the wall/roof (EPS$_{mid}$), and the EPS is in contact with the interior (EPS$_{int}$). The thermal properties of the materials are shown in Table 1.

Table 1: Thermal properties of the different materials used in the simulations, high density concrete (HDC), aerated concrete (AeC), and expanded polystyrene foam (EPS) [21].

Material	k	ρ	c	α
	$W/(mK)$	kg/m^3	$J/(kgK)$	m^2/s
HDC	2.00	2400	1000	0.833×10^{-6}
AeC	0.12	550	1004	0.217×10^{-6}
EPS	0.04	15	1400	1.900×10^{-6}

For both cases (A/C and nA/C) two sets of numerical simulations are carried out. In the first set the width of the roof L is varied from $0.10m$ to $0.20m$ for the monolayered roofs and in the second set the six roof configurations are compared, all with $L = 0.10m$.

3.1. Air-conditioned room

In Fig. 1 the daily energy per unit area E needed to keep the room at the comfort temperature ($T_c = 28.4^oC$) for the three monolayered roofs is presented as a function of the roof width L. As expected, E decreases as L increases. The best thermal performance (lowest E value) is achieved by the EPS roof. In this case doubling L from $0.10m$ reduces E by 50%. For $L = 0.10m$, the value of E of the EPS roof is more than seven times smaller than that of the HDC roof and two times smaller than that of the AeC roof. Analyzing the values of the thermal conductivity (relevant in boundary conditions) and of the thermal diffusivity (relevant in the bulk) of these three

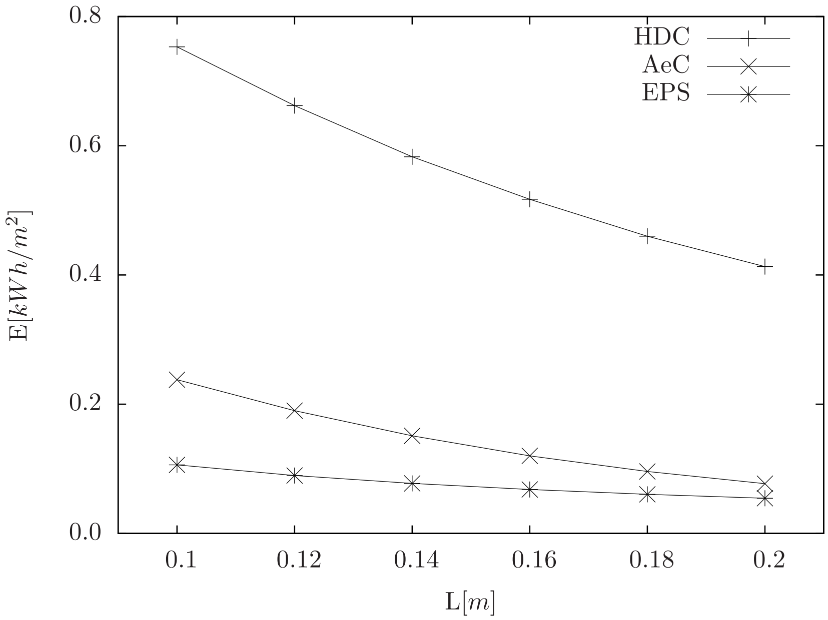

Figure 1: Daily energy per unit area E of air-conditioned rooms for the three monolayered roofs as a function of the width L.

materials (Table 1) and comparing E, it is found that for the A/C room, the thermal conductivity value has the main effect over the heat transfer. To decrease E, k must be as low as possible.

The E values for the three monolayered and the three multilayered roofs are compared in Fig. 2 all with $L = 0.10m$. The best thermal performance is for the monolayered EPS roof and the worst is for the monolayered HDC roof. Replacing a small layer of the HDC roof with a EPS layer reduces the energy consumption. Of the three multilayered roofs, the best thermal performance is obtained when the EPS layer is in the outside (EPS$_{ext}$). Its E value is 27% of that of the HDC roof. Locating the EPS in the middle (EPS$_{mid}$) or the interior side of the roof (EPS$_{int}$) E is 34% and 35% of the energy needed by the HDC roof, respectively.

3.2. Non air-conditioned room

In Fig. 3 the indoor air temperature T_{in} as a function of time for the three monolayered roofs with $L = 0.10m$ is presented, the outdoor air and the sol-air temperatures are included. The amplitude of the indoor air temperature

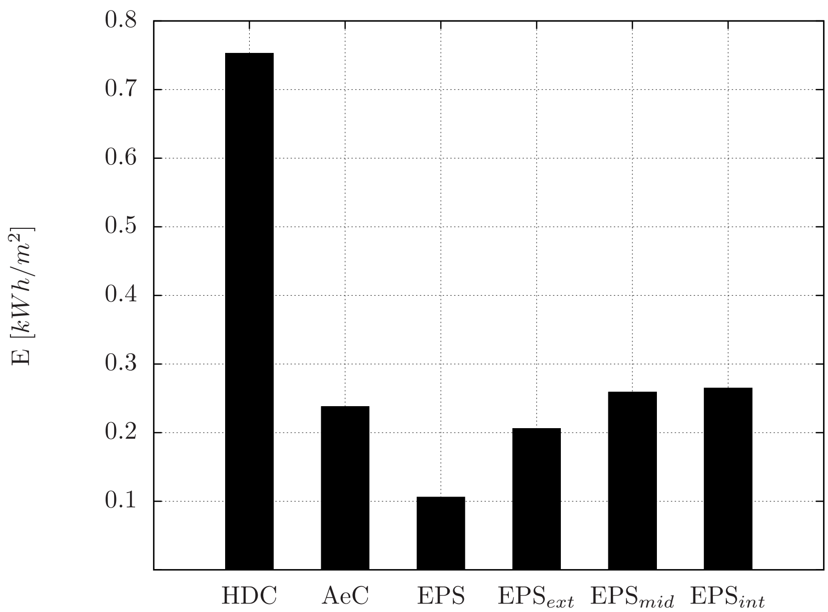

Figure 2: Daily energy per unit area E of air-conditioned rooms for the mono and multi-layered roofs with $L = 0.10m$.

for the EPS roof is larger than that of the AeC and HDC roofs and also larger than the amplitude of the temperature of the outdoor air. For the AeC roof the difference between the maximum and minimum indoor air temperature is of the order of $5°C$ while in the EPS roof is of more than $30°C$. The variations of the decrement factor DF and the lag time LT as the roof width L changes are shown in Figs. 4 and 5. The AeC roof has a DF slightly lower than that of the HDC roof and significantly lower than the EPS roof. For $L = 0.10m$ the AeC roof DF is about 60% of the corresponding value of the EPS roof and for $L = 0.20m$ the relation is roughly 23%. The LT value of the AeC roof increases from $5h$ to $10h$ as L increases from $0.10m$ to $0.20m$. For the same widths the LT of the EPS only increases from $2.8h$ to $3.1h$. The AeC roof, with the lowest DF and the largest LT, gives the best thermal performance of the three monolayered roofs considered.

Analyzing the values of the thermal conductivity (relevant in boundary conditions) and of the thermal diffusivity (relevant in the bulk) of these three materials (Table 1) and comparing the values of DF and LT for each roof, the results indicate that for the nA/C room, the heat transfer is mainly governed by the thermal diffusivity. To increase DF and LT, α must be as low as possible.

The decrement factor DF and the lag time LT results for the monolayered and the multilayered roofs are presented in Figs. 6 and 7. The DF of the EPS_{ext} is almost four times lower than the best monolayered roof (AeC). The EPS_{mid} has also lower DF than the monolayered roofs but the EPS_{int} has a DF not only larger than that of the AeC roof but also larger than the HDC roof. This shows that in a nA/C room the position of the insulation is important. The largest LT is for the EPS_{mid} roof ($6.5h$), followed by the AeC roof. Since the DF of the EPS_{ext} is of the order of 0.1, its LT value, as previously mentioned, is not important. From these results, the best thermal performance is that of an EPS_{ext} roof with the lowest DF and a non-relevant LT, and the second best is the EPS_{mid} roof with the second lowest DF and the largest LT.

3.3. Air-conditioning transient operation

As expected, for the three monolayered roofs Δt_c decreases as L increases. But there is not a general best configuration for the transient operation. The best thermal performance among the six tested roofs depends on the temperature of the air from the air-conditioning plant $T_{A/C}$, the air changes C, and the turn on time t_{on}.

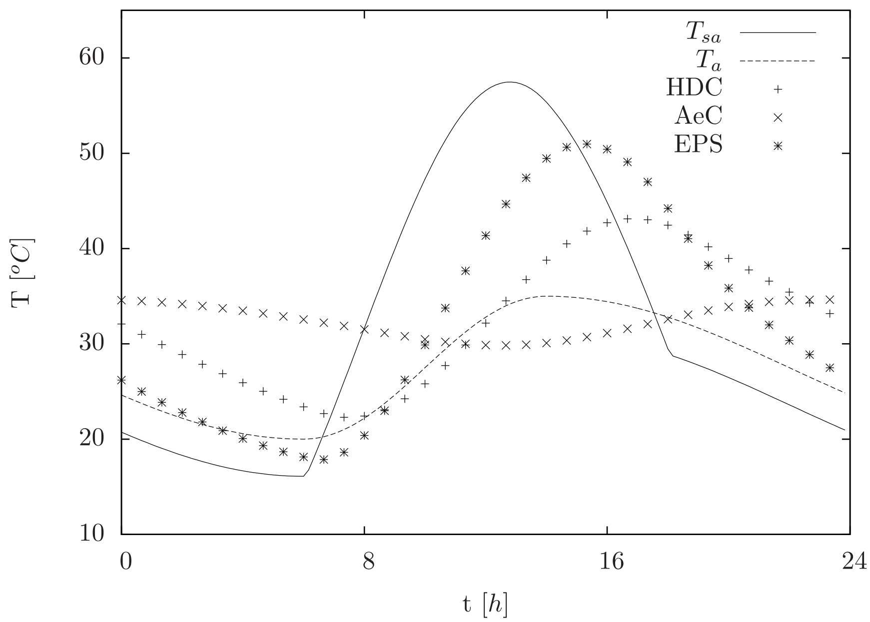

Figure 3: Indoor air temperature of the non-air-conditioned room for the three monolayered roofs with $L = 0.10m$, temperature of the outdoor air T_a, and sol-air temperature T_{sa} as function of time.

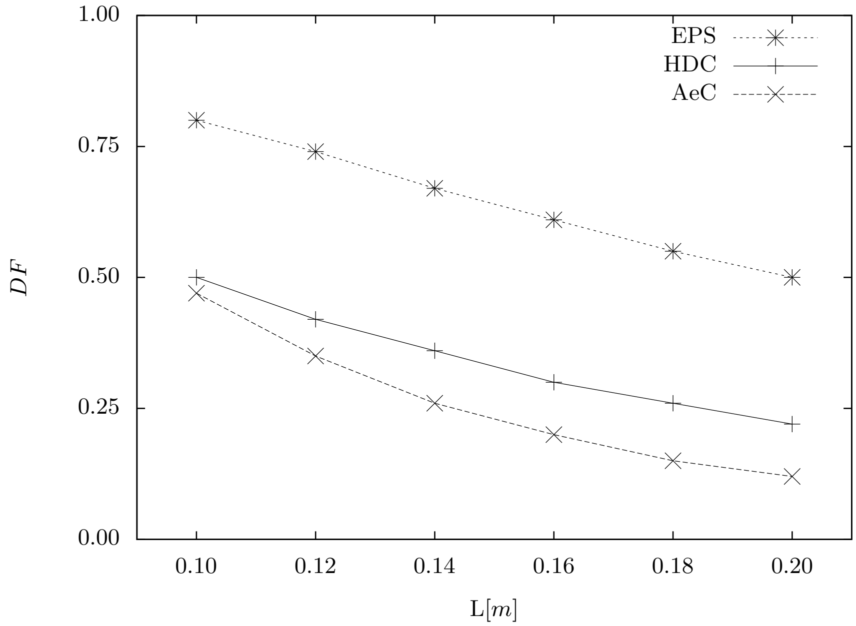

Figure 4: Decrement factor DF of a non-air-conditioned room for the three monolayered roofs as a function of the width of the roof L.

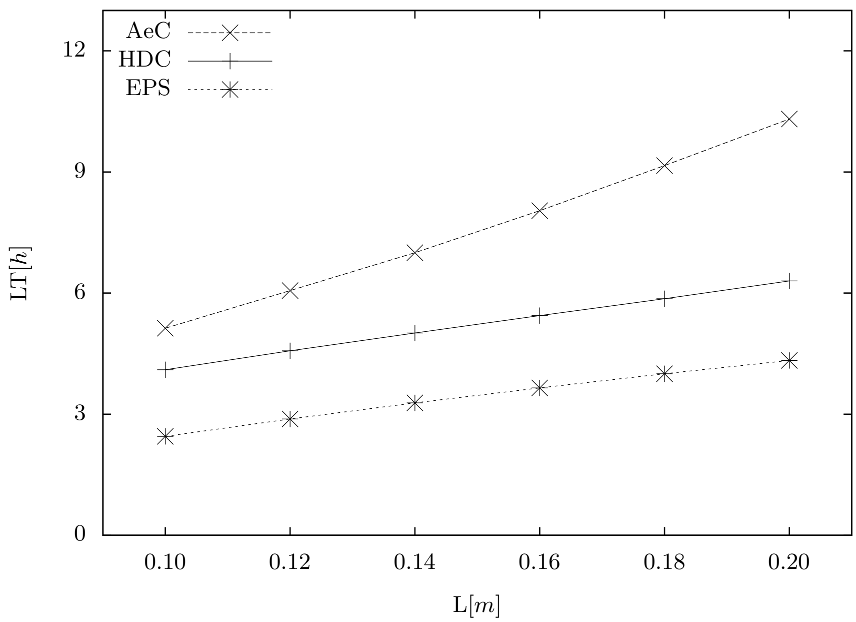

Figure 5: Lag time LT of a non-air-conditioned room for the three monolayered roofs as a function of the width of the roof L.

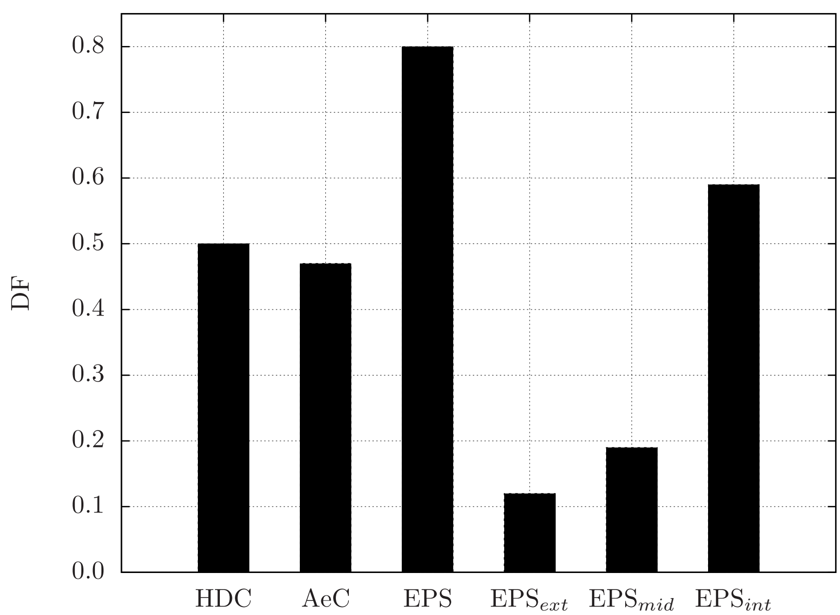

Figure 6: Decrement factor DF of a non-air-conditioned room for the mono and multilayered roofs with a width $L = 0.10m$.

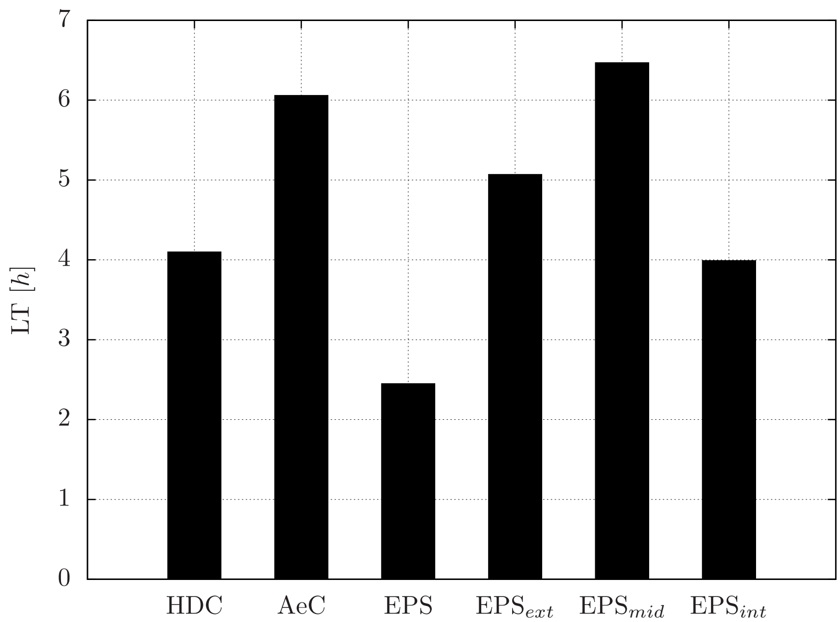

Figure 7: Lag time LT of a non-air-conditioned room for the for the mono and multilayered roofs with a width $L = 0.10m$.

4. Conclusions

In this work the thermal performance of three monolayered and three multilayered roofs for air-conditioned (A/C) and non air-conditioned (nA/C) rooms are analyzed. For the A/C case the daily energy per unit area needed to keep the room at the comfort temperature is used as the thermal performance parameter. The parameters used for the nA/C case are the decrement factor and the lag time. The main conclusion of this work is that the thermal performance of a wall/roof depends on the room conditions, whether air conditioned or not. An appropriate wall/roof for an air-conditioned room may not be suitable for a non air-conditioned one.

In the A/C case the best thermal performance is obtained with an expanded polystyrene foam (EPS) monolayered roof, the second one is a roof composed by high density concrete roof (HDC) plus EPS in contact with the exterior (EPS_{ext}) and the worst with a HDC monolayered roof. In the nA/C case the best option is an EPS_{ext} roof and the worst is an EPS monolayered roof. In this case the position of the EPS insulation layer with respect to the HDC layer is important. A good compromise in both the A/C and nA/C cases is the EPS_{ext} roof.

It can be concluded that for the A/C case the most important physical property of a monolayered wall/roof is the thermal conductivity, which must be as low as possible, and that for the nA/C case the most important physical property is the thermal diffusivity, which must be as low as possible. According to Ozel and Pihtili's results [13], it is expected that these conclusions are valid for walls/roofs with different orientations and under different climatic conditions.

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