Thermal performance of envelope wall/roofs of intermittent air-conditioned rooms

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Abstract

The thermal performance of six wall/roof configurations in an intermittent air-conditioned room, in a climate where the outdoor temperature or the sol-air temperature swing crosses the thermal comfort zone, was numerically evaluated. The intermittent air-conditioning system operates heating or cooling. When operating for cooling it is turned on when the indoor temperature is greater than the upper comfort temperature and when operating for heating it is turned on if the indoor temperature is smaller than the lower comfort temperature; otherwise it remains off. A one dimensional heat transfer model with periodic outdoor conditions was considered. The parameters used to evaluate the configurations are the energy for the on-periods and a thermal index during the off-periods. For comparison purposes, the wall/roof configurations were also evaluated in an air-conditioned room where the temperature was kept constant full time. The results show that the thermal evaluation of a wall/roof must be done taking into account the operation condition of the air-conditioning system.

Keywords: wall/roof thermal performance, intermittent air-conditioned, numerical simulations

1. Introduction

The envelope walls and roofs are important components to be considered for the thermal analysis of buildings, as well as ventilation, direct solar gains through windows, etc. To isolate the thermal effect of the envelope

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walls/roofs, the studies have disregarded other factors affecting the building thermal performance. In general, when evaluating the thermal performance of envelope walls and roofs, research interest has focused to find a suitable configuration of a wall/roof for air-conditioned rooms, considering the indoor air temperature of the room constant.

Many authors have analitically studied the one-dimensional heat transfer through a wall/roof with periodic outdoor temperature under convection boundary conditions, for air-conditioned rooms [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. In all these studies, material properties and indoor and outdoor surfaces film coefficients have been considered constant. In general, analytical methods are limited in the number of layers.

Numerical methods have also been used to solve the one-dimensional heat transfer equation through monolayered and multilayered wall/roofs. As in the analytical studies, the material properties and indoor and outdoor surfaces film coefficients have been considered constant. Chen and Krokosky [11] 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 their numerical results with experiments, showing that the finite element technique gives better results than the Mackey and Wright method for multilayered roofs [3].

The effect of monolayered or multilayered wall/roof configurations in air-conditioned rooms has been studied numerically. Most of the studies have used the decrement factor and time lag as evaluation parameters [12, 13, 14, 15, 16, 17, 18, 19, 20]. The energy consumed to maintain constant the indoor air temperature has also been used as evaluation parameter [21, 18, 17, 20]. It is clear that as the value of this energy is lower the thermal performance of the wall/roof is better. The decrement factor measures the amplitude of the indoor surface temperature oscillation with respect to the amplitude of the outdoor surface temperature oscillation. The time difference between the maxima of the indoor surface temperature and the outdoor surface temperature is the time lag. A wall/roof has a better thermal performance as the decrement factor is reduced and the time lag is increased. Asan and Sancaktar [12] found that a decrease in the thermal conductivity or an increase in the heat capacity of a monolayered wall/roof decreases the decrement factor and increases the time lag. They showed that including an insulation layer decreases the decrement factor and increases the time lag. Asan [13] computed decrement factors and time lags for monolayered wall/roofs. Twenty-six different building materials and eight different thicknesses of the wall/roof were studied. As expected, for all materials the decrement factor decreases as the thickness increases and the time lag increases as the thickness increases. Studies have shown that placing an insulation layer on the wall/roof exterior side gives a better thermal performance than placing the insulation layer on the wall/roof interior side [14, 16, 19]. For wall/roofs made of a high thermal capacity material and constant amounts of insulation material divided in layers, an increase in the number of layers increases the thermal performance [16, 17]. Barrios *et al* [18] found that monolayered wall/roofs made of an insulation material have a better thermal performance than wall/roofs of the same thickness made of a high thermal capacity material with a layer of an insulation material placed on the exterior side, in the middle or the interior side. Some studies have shown the importance of the effect of the solar absorptivity of the outdoor surface in the heat transfer through multilayered wall/roofs [15, 20]. Three-dimensional ANSYS simulations have been used to study the reduction in energy consumption by incorporating insulation in the wall [21].

For non air-conditioned rooms, the thermal behavior of a wall/roof was analyzed considering the indoor air temperature only as a function of the heat transfer through it [18]. The results show that monolayered wall/roof made only of insulation material appropriate for an air-conditioned room, has a poor thermal performance in non air-conditioned rooms. It was also found that placing an insulation layer on the wall/roof exterior side has a better thermal performance than placing it on the interior side. This result is the same than the corresponding one for air-conditioned rooms [14, 16, 19].

The thermal behavior of an intermittent heated room was studied by Tsilingiris [22] in a cold climate in which the outdoor temperature does not cross the thermal comfort zone and solar radiation is low. He reported that, for walls/roofs having the same proportions of insulation material and high thermal capacity material, placing an insulation layer in the interior side of the wall/roof, irrespective of the heating start time and duration, resulted in the lowest energy consumption needed to keep the indoor air temperature constant.

Assumption of a constant indoor air temperature is suitable for continuous operation of an air-conditioning system in climates where daytime outdoor air temperature does not cross the thermal comfort zone and the air-conditioning system heats (or cools) the indoor air full time. In regions with climatic conditions where the daytime outdoor air temperature or the sol-air temperature crosses the thermal comfort zone during a day, this assumption implies that the air-conditioning system is capable of automatically heating or cooling, as required, to keep the indoor air temperature constant. However this is not the common way air-conditioning systems operate in some countries like Mexico. Rather, they operate intermittently heating or cooling: the system is turned on when the indoor temperature is greater than the upper comfort temperature (cooling) or when the indoor temperature is smaller than the lower comfort temperature (heating), otherwise it remains off. It has been demonstrated that a good wall/roof configuration in an air-conditioned room could be not suitable for a non air-conditioned room [18]. Thus, it is necessary to evaluate the thermal performance of the configurations in an intermittent air-conditioned room for a climate in which the outdoor air or sol-air temperature crosses the thermal comfort zone.

The aim of this work is to analyze the thermal performance of different configurations for a wall/roof in an intermittent air-conditioned room (iA/C), where the outdoor temperature or the sol-air temperature swing crosses the thermal comfort zone and the constant indoor temperature assumption is not applicable. A one dimensional heat transfer model with periodic outdoor conditions is numerically solved using an explicit control volume scheme. The material properties and the outdoor and indoor film heat transfer coefficients are assumed to be constant. The energy used during the on-periods and the thermal index during the off-periods are measured. For comparison purposes, the energy consumed for full air-conditioned condition (A/C), i.e. keeping the indoor air temperature constant, is also reported.

2. Model

In order to achieve the aim of the work, only the effect of the envelope wall/roof is considered in the heat transfer model. Moisture transfer is disregarded because the interest is focused in the thermal evaluation of wall/roofs configurations with contrasting thermal properties. The one dimensional heat transfer model used in this research is similar to that used in Ref. [18]. The corresponding equation for a wall or a roof composed by N layers of a total thickness L is

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

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

Between layers, the following condition is satisfied

$$k_j \left.\frac{\partial T}{\partial x}\right|_{j,j+1} = k_{j+1} \left.\frac{\partial T}{\partial x}\right|_{j,j+1}, \tag{2}$$

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 layers.

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} is the film heat transfer coefficient and $T_{x=0}$ is the surface temperature at the outdoor side. The sol-air temperature T_{sa} is defined by [23] as

$$T_{sa} = T_a + I\frac{a}{h_{out}} - RF, \tag{4}$$

where $T_a(t)$ is the temperature of the outdoor air, $I(t)$ is the solar radiation, a the solar absorptivity of the outdoor surface, and RF is the infrared radiation factor on an average day [23].

The indoor boundary condition is

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

where h_{in} is the film heat transfer coefficient, $T_{x=L}$ is the indoor surface temperature and T_{in} is the indoor air temperature which is kept constant when the air conditioning is on.

For iA/C rooms, when the air conditioning is off, the indoor air temperature is a function of the heat transfer through the wall, and is calculated by

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

where ρ_a and c_a are the air density and specific heat and d is the distance to where an adiabatic condition is assumed ($d \gg L$). When the air conditioning is on for the iA/C rooms, the indoor air temperature is kept constant and

Eq. (5) is used. This equation relates the temporal change in thermal energy of the air inside a room and the heat transfer through the wall/roof. Inside the room perfect mixing is assumed.

To obtain a periodic solution an iterative process is used until $|T(x,t_r) - T(x,t_r+24)| < 0.1$ for all x, where T is in degree Celsius (^oC) and t_r in hours. The initial condition for $T(x,0)$ is the mean outdoor temperature.

For A/C rooms, T_{in} in Eq. (5) is kept constant at the upper comfort limit, $T_c + \Delta T_c$, when cooling, and at the lower comfort limit, $T_c - \Delta T_c$, when heating. In these expressions ΔT_c is the amplitude of the thermal comfort zone [24], and T_c is the comfort temperature, defined as [25]

$$T_c = 13.5^oC + 0.54 T_{am}, \tag{7}$$

where T_{am} is the outdoor air mean temperature for a typical day of the month.

For both the A/C and iA/C rooms, the energy per unit area consumed in a day (or year) is calculated

$$E = \sum_i h_{in} \Delta t_i |(T_{in} - T_{x=L})|, \tag{8}$$

where Δt_i is the numerical time step. The summation is taken for the i-th values during a day (or year). To complement the thermal evaluation of a wall/roof in an intermittent air-conditioned cooled room (iA/C$_c$) in addition to the energy, a cold thermal index is used and is defined as

$$I_c = \sum_i \Delta t_i (T_c - \Delta T_c - T_{in}), \tag{9}$$

while $T_{in} < T_c - \Delta T_c$. To evaluate a wall/roof in an intermittent air-conditioned heated room (iA/C$_h$), the hot thermal index during a day (or year) is defined as

$$I_h = \sum_i \Delta t_i (T_{in} - T_c - \Delta T_c), \tag{10}$$

while $T_{in} > T_c + \Delta T_c$. The units are are h^oC/day (or $h^oC/year$). This index measures how far is the indoor temperature T_{in} from the set-point of the air-conditioning system. A smaller value indicates a better thermal performance for an intermittent air-conditioned room.

3. Numerical simulations

The numerical simulations were performed considering a horizontal roof with $RF = 3.9°C$ [23]. The maximum and minimum ambient temperatures and the radiation peak, for a typical day of each month of a year, were taken from Meteonorm [26] for Torreón, Coahuila, México. The outdoor temperature model [27] reproduces the typical temperature behavior in hot-dry climates like the one of Torreón. In this model the maximum and minimum values of T_a and the times when they occur must be given. The minimum value of T_a is assumed to happen at sunrise [28]. The solar radiation was approximated by a sinusoid with its maximum at the corresponding solar midday. The outside and inside film heat transfer coefficients are $h_{out} = 13W/m^2\,°C$ and $h_{in} = 6.6W/m^2\,°C$ [29], respectively. The absorptivity of the exterior surface is $a = 0.4$ (Gray color) [30]. As an approximation, the ground is considered adiabatic, thus $d = 2.5m$. The set-point for the intermittent air-conditioned cooled room (iA/C$_c$) is the upper limit of the comfort temperature ($T_c + \Delta T_c$) and the set-point for the intermittent air-conditioned heated room (iA/C$_h$) is the lower limit ($T_c - \Delta T_c$).

The numerical parameters for the simulations are the following. Each control volume has a length $\Delta x = 0.001m$ with a total of 100 control volumes for each roof configuration. In order to have numerical stability, the time step is

$$\Delta t = 0.1\Delta t_{min} \tag{11}$$

where Δt_{min} is the minimum of the Δt_j for all $j = 1, \ldots, N$ and

$$\Delta t_j = \frac{\rho_j c_j (\Delta x)^2}{2k_j}. \tag{12}$$

In the last equation, ρ_j, c_j, and k_j are the density, specific heat and thermal conductivity of the j-th layer, respectively [31].

Six roof configurations, all with a total thickness of $0.10m$, were considered and the descriptions are shown in Table 1. These are the same configuration that were evaluated in [18].

The thermal properties of the high density concrete (HDC), aerated concrete (AeC) and expanded polystyrene foam (EPS) are shown in Table 2.

Table 1: Roof configurations from outside to inside using high density concrete (HDC), expanded polystyrene foam (EPS) and mortar (M).

Configuration	Description
HDC	High density concrete $0.10m$
AeC	Aereated concrete $0.10m$
EPS	Expanded polystyrene foam $0.10m$
EPS_{ext}	EPS $0.02m$ + HDC $0.08m$
EPS_{mid}	HDC $0.04m$ + EPS $0.02m$ + HDC 0.04
EPS_{int}	HDC $0.08m$ + EPS $0.02m$

Table 2: Thermal properties of the different materials used in the simulations, high density concrete (HDC), expanded polystyrene foam (EPS) and mortar (M) [32].

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}

4. Results

The indoor air temperature for a roof made of EPS in an iA/C$_c$ room, the outdoor and the sol-air temperatures for May are presented in Fig. 1 (a). The horizontal solid lines delimit the thermal comfort zone. As can be observed, the outdoor temperature and the sol-air temperature cross the thermal comfort zone. The indoor air temperature from midnight to about approximately 9h is below the lower comfort limit, contributing to the cold thermal index. There is a short period in which the indoor temperature is within the comfort zone. After that, the cooling air conditioning set point is reached and the temperature is kept constant. The iA/C$_c$ is on from approximately 10h to 19h, with an energy consumption of $0.007kWh/m^2day$. In the afternoon outdoor and sol-air temperatures decrease. At about 19h the sol-air temperature is below the upper comfort limit and the air conditioning is no longer required. The indoor temperature is within the comfort zone from 19h to 23h; after 23h the indoor temperature is below the lower comfort zone limit making a small contribution to the cold thermal index.

The indoor air temperature for a roof made of EPS in an iA/C$_h$ room, together with the outdoor and sol-air temperature for December, are presented in Fig. 1 (b). For this month, the outdoor temperature reaches the thermal comfort zone during some hours and the sol-air temperature does cross the thermal comfort zone. The indoor air temperature from midnight to about 9h is below the lower comfort limit, so the air-conditioning system is turned on to heat. From approximately 9h to 12h the indoor air temperature is within the comfort zone. Then, from about 12h to 19h, the indoor air temperature is greater than the upper comfort limit, contributing to the hot thermal index. From 10h to 18h, the indoor air temperature is within the comfort zone. Then, from 19h to the end of the day, the indoor air temperature is kept at the lower comfort limit.

Simulations of the six configurations for the twelve months of the year were carried out for an intermittent air-conditioned cooled room (iA/C$_c$) and a full time air-conditioned room (A/C). The energy per unit area per day for iA/C$_c$, EiA/C_c, the cold thermal index per day for iA/C$_c$, I_c, and the energy per unit area per day for A/C, EA/C, are presented in Fig. 2 (a) to Fig. 2 (f). As can be seen from these figures, in an iA/C$_c$ room, the energy used decreases in the cold months and increases in hot months and the cold thermal index increases in the cold months and decreases in the hot months, as expected for an intermittent air-conditioning system. For A/C rooms, the energy needed to keep the indoor temperature constant has two peaks for all configurations, one in May and the other in December. This happens because the outdoor or sol-air temperature crosses the thermal comfort zone and the A/C system has to cool during May and heat during December. This fact is more evident for configuration HDC (Fig. 2a). For some configurations the energy consumed for iA/C$_c$ is zero during winter, EPS$_{ext}$ during five months, EPS$_{mid}$ during four months, HDC and AeC during two months. The cold thermal index I_c is zero during the hot months for some configurations, EPS$_{ext}$ during six months, EPS$_{mid}$ during one month.

When ordering the roof configurations from best to worst as a function of the energy consumed for the iA/C$_c$, the order is EPS, EPS$_{ext}$, AeC, EPS$_{mid}$, EPS$_{int}$, and HDC, for the hot months (April, May, June, July) and changes slightly for the rest of the months. The cold thermal index keeps the same order except for two of the coldest months (January and December). For the A/C, the order from best to worst is the same for all months, EPS, EPS$_{ext}$, AeC, EPS$_{int}$, EPS$_{mid}$, and HDC.

For an annual evaluation of the six configurations, EiA/C_c, I_c, and EA/C are shown in Fig. 3. For the iA/C$_c$ room, using energy for cooling as the only

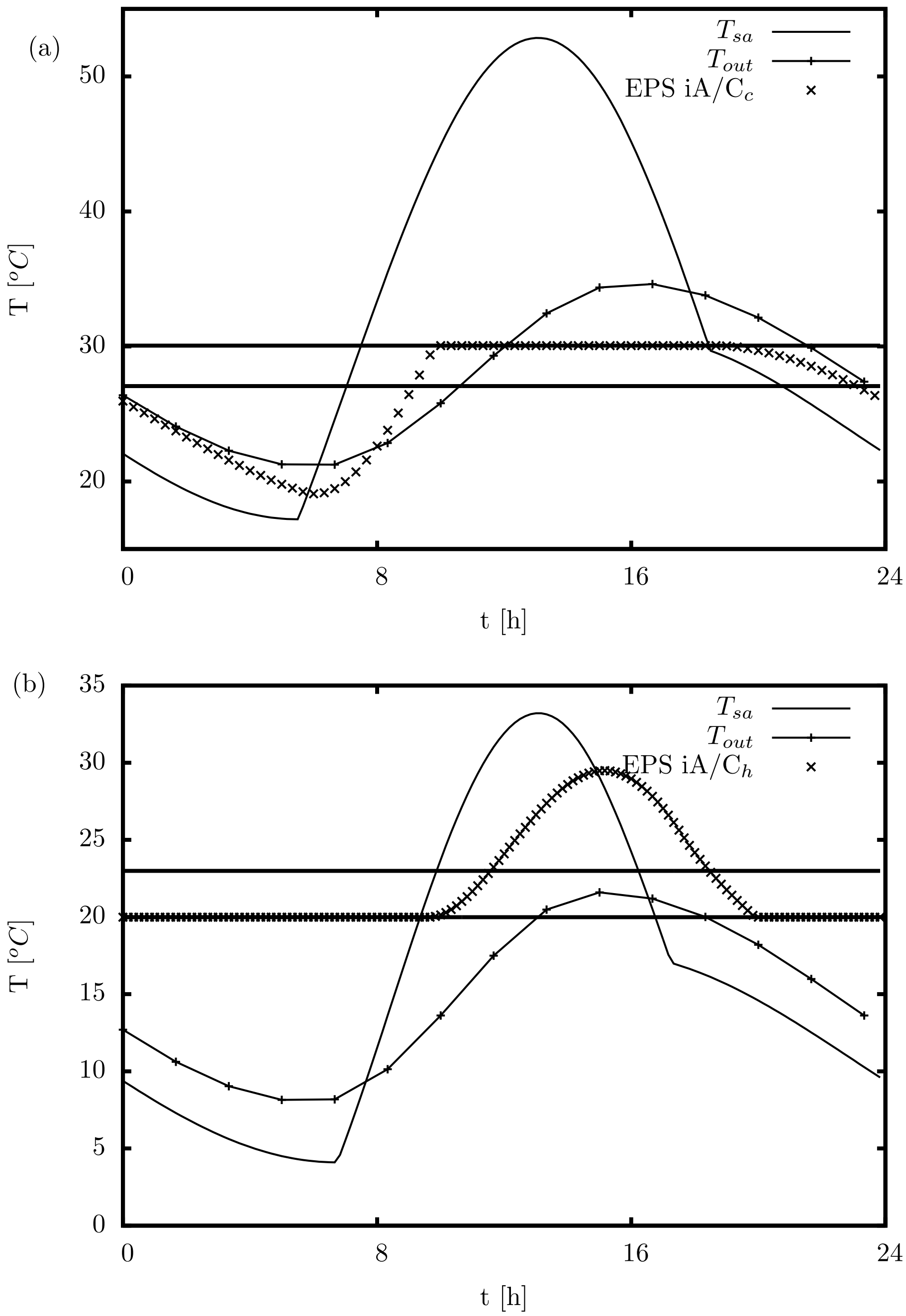

Figure 1: Indoor air temperature for (a) intermittent air-conditioned cooled room (iA/C$_c$) in May and for an (b) intermittent air-conditioned heated room (iA/C$_h$) for a roof made of 0.10m of EPS in December and the sol-air temperature T_{sa} as function of the time of day. The two horizontal solid lines correspond to the upper and lower limit of the thermal comfort zone.

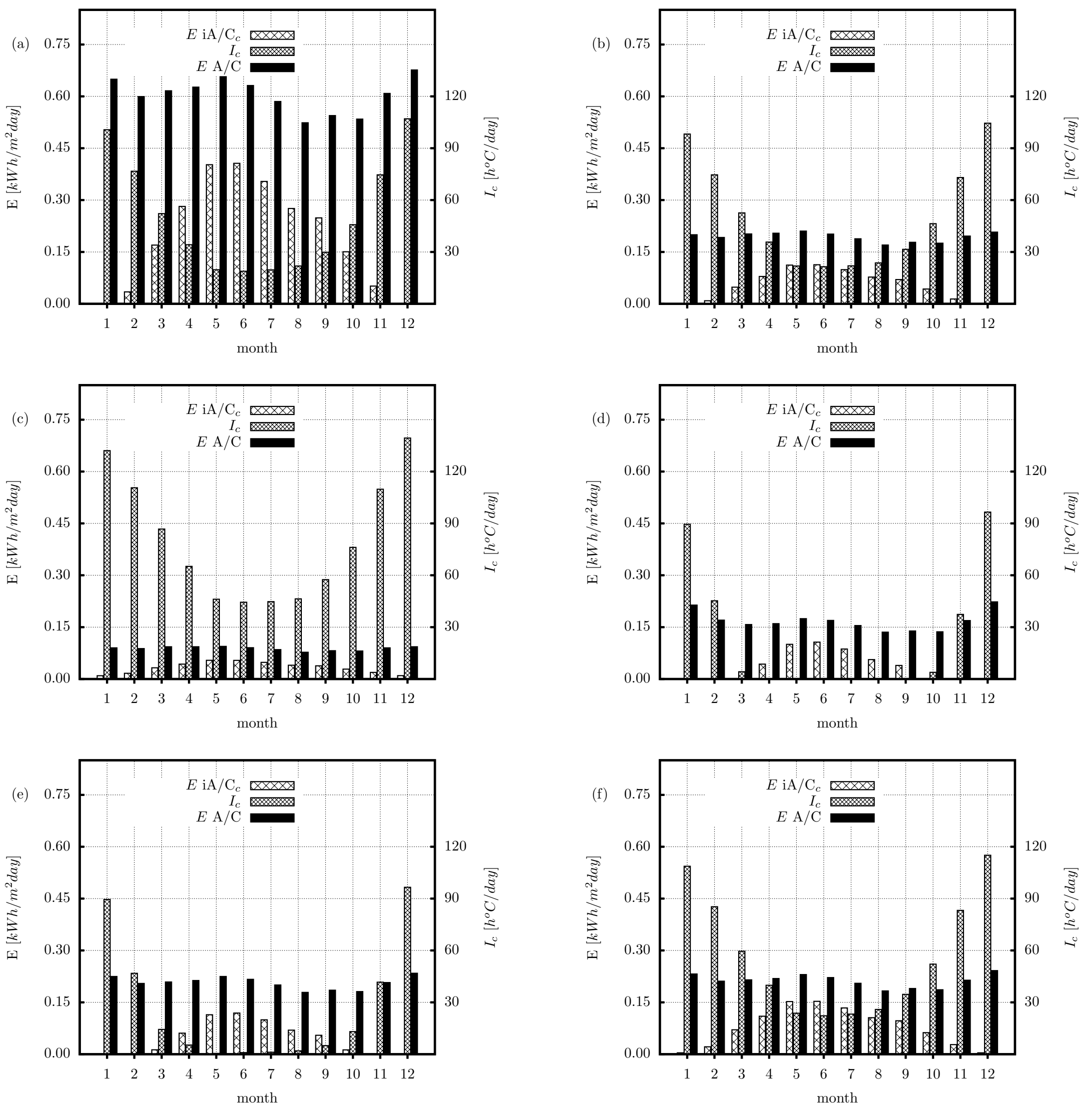

Figure 2: Energy per unit area and per day and thermal index per day in intermittent air-conditioned cooled rooms, $E\ iA/C_c$ and $I_c\ iA/C_c$, and energy per unit area and per day for air conditioned rooms, $E\ A/C$, during the twelve months of the year. All six configurations are shown, corresponding to (a) HDC, (b) AeC, (c) EPS, (d) EPS$_{ext}$, (e) EPS$_{mid}$, and (f) EPS$_{int}$.

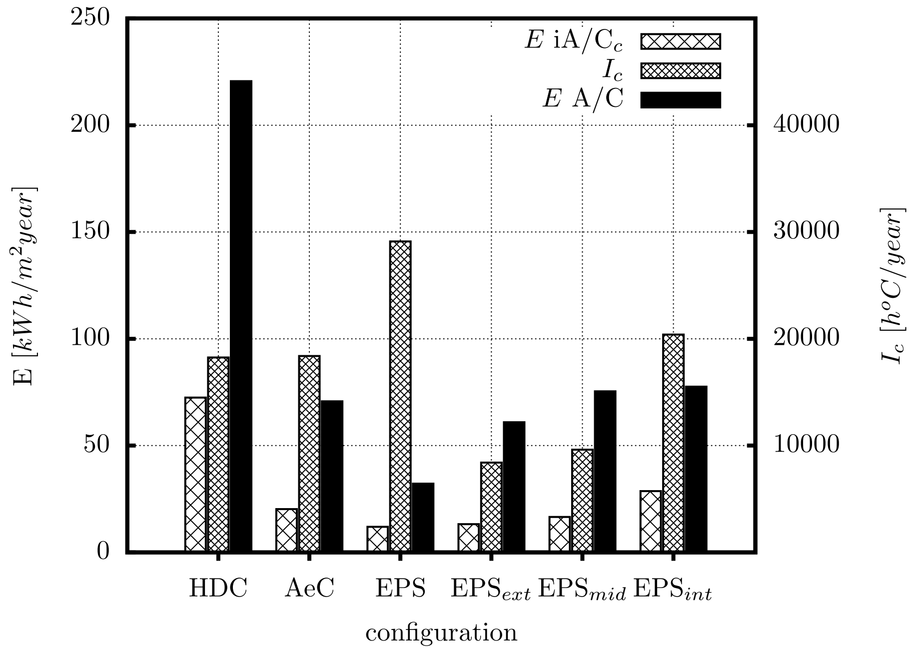

Figure 3: Energy per unit area used annually and thermal index for intermittent air-conditioned cooled rooms E iA/C$_c$ and I_c A/C$_c$, and energy per unit area used annually for air-conditioned rooms E A/C. For the six configurations.

criterion, the order of configurations, from best to worst, is: EPS, EPS$_{ext}$, EPS$_{mid}$, AeC, EPS$_{int}$, and HDC. For A/C rooms the order of configurations is: EPS, EPS$_{ext}$, AeC, EPS$_{int}$, EPS$_{mid}$, and HDC. The best to worst order of configurations for an iA/C$_c$ room is different than for an A/C room. As previously mentioned, in an iA/C$_c$ room the indoor temperature during the day can be below the lower comfort limit, therefore, the thermal index must also be considered. The EPS has the lowest energy consumption but the highest cold thermal index. Considering that those configurations with a cold thermal index greater than $10,500h^oC/year = 1.2^oC$ and with an energy consumption greater than $73kWh/m^2year = 8.2W/m^2$ are not suitable, the order of the configurations from best to worst in the iA/C$_c$ room is EPS$_{ext}$ and EPS$_{mid}$.

The energy and the hot thermal index were obtained for an intermittent air-conditioned heated room (iA/C$_h$) during a cold month (December). The results are presented in Fig. 4 (a). To analyze the behavior of configurations in heating and cooling conditions, the results of an intermittent air-conditioned cooled room (iA/C$_c$) corresponding to a hot month (May) were included in Fig. 4 (b). The configurations with a thermal index greater than $29h^oC/day = 1.2^oC$ and an energy consumption greater than $0.2kWh/m^2/day = 8.2W/m^2$ are considered to be not suitable. The order of configurations for both heating and cooling operation conditions is the same: EPS$_{ext}$, EPS$_{mid}$, AeC, and EPS$_{int}$. The first two configurations have the same order as in the annual analysis and are the only ones that fulfill the energy and thermal index criteria in the annual analysis.

When the air-conditioning systems work only for heating or for cooling, performing the evaluation of a wall/roof considering the indoor temperature constant may lead to choose not the appropriate configuration.

5. Conclusions

The thermal performance of six configurations of a roof in an intermittent air-conditioned room (iA/C) in a climate where the outdoor temperature or sol-air temperature swing crosses the thermal comfort zone was numerically studied using a one dimensional heat transfer model with periodic outdoor conditions. For an intermittent air-conditioned room two parameters must be used to evaluate the configurations, the energy consumption during on-periods and the thermal index during off-periods. The evaluation was also performed in a full time air-conditioned room (A/C) where the indoor air temperature is kept constant. In this case, the energy is the only evaluation parameter.

The order of the wall/roof configurations for the intermittent air-conditioned cooled room can vary along the year. Therefore, if this system is going to be used all the year, an annual evaluation must be done, otherwise the evalution must be performed for the specific season of use.

For the wall/roof configurations studied in Torreón climate for an iA/C room, the optimal configuration based on the annual performance is the one made of high density concrete with an insulation polystyrene foam layer placed in the exterior (EPS$_{ext}$), followed by a high density concrete with the polystyrene foam layer placed in the middle (EPS$_{mid}$). The order from best to worst are the same as the configurations reported by Barrios et al [18] for a non air-conditioned room and are different to the order considering a full time air-conditioning system.

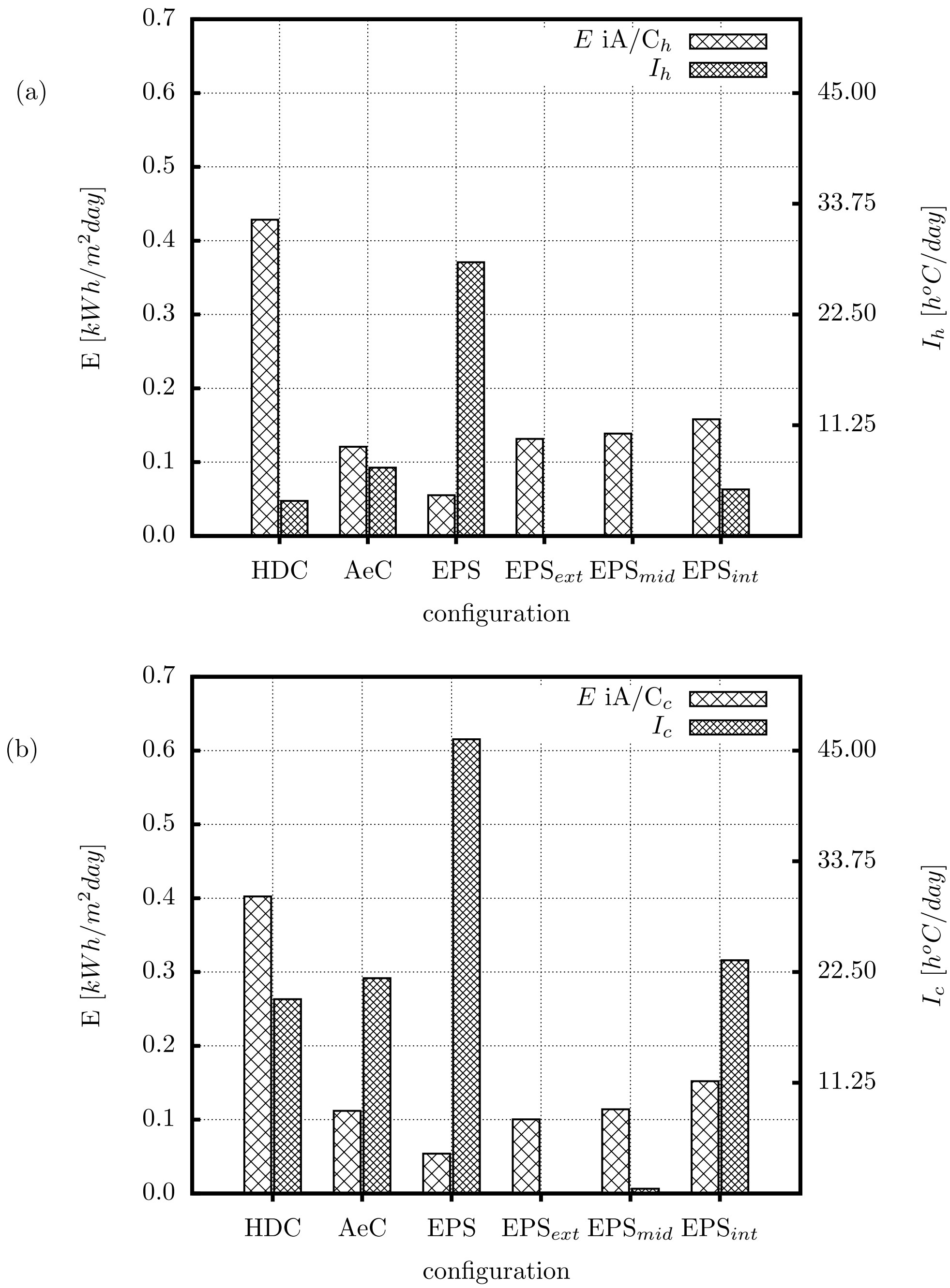

Figure 4: Energy used per unit area per day and thermal index for the six configurations for (a) a typical day of December and (b) for a typical day of May.

The results show that when using one small layer of insulation in a wall/roof, the best thermal performance in an intermittent air-conditioned cooled or heated room is achieved by placing it at the exterior side. Tsilingiris [22] reported that in an intermittent air-conditioned heated room, the best place to locate the insulation layer is in the interior side. This result was obtained in a cold climate where the outdoor temperature swing does not cross the thermal comfort zone and the solar radiation was low.

The main conclusion of the present work is that the selection of the wall/roof configuration must be done performing the thermal evaluation under the real operating condition of the air-conditioning system, intermittent or full time.

Acknowledgements

Partial economic support from CONACyT-SENER 118665 and CONACyT-Morelos 93693 projects are acknowledged.

References

[1] J. S. Alford, J. E. Ryan, F. O. Urban, Effect of heat storage and variation in indoor temperature and solar intensity on heat transfer through walls, ASHVE Trans 45 (1935) 369–396.

[2] C. O. Mackey, L. T. Wright, Periodic heat flow - homogeous walls or roofs, ASHVE Trans. 50 (1944) 293–312.

[3] C. O. Mackey, L. T. Wright, Periodic heat flow - composite walls or roofs, ASHVE Trans. 52 (1946) 283–296.

[4] D. G. Stephenson, G. Mitalas, Calculation of heat conduction transfer functions for multi-layer slabs, ASHVE Trans. 77 (1971) 117–126.

[5] T. Kusuda, Thermal response factors for multilayer structures of various heat conduction systems, ASHRAE Trans 75 (1969) 246–279.

[6] H. Ceylan, G. Myers, Long-time solutions to heat conduction transients with time-dependent inputs, ASME Journal of Heat Transfer 102 (1980) 115–120.

[7] K. Ouyang, F. Haghighat, A procedure for calculating thermal response factors of multi-layered walls - state space method, Building and Environment 26 (1991) 173–177.

[8] A. K. Athienitis, Thermal analysis of buildings in a mathematical programming environment and applications, Building and Environment 34 (1999) 401–415.

[9] R. Yumrutas, M. nsal, M. Kanoglu, Periodic solution of transient heat flow through multilayer walls and flat roofs by complex finite fourier transform technique, Building and Environment 40 (2005) 1117–1125. Cited By (since 1996): 14.

[10] R. Yumrutaş, Kaşka, E. Yildirim, Estimation of total equivalent temperature difference values for multilayer walls and flat roofs by using periodic solutions, Building and Environment 42 (2007) 1878–1885.

[11] C. H. Chen, E. M. Krokosky, Steady and non steady solar heat transmission through roofs, Materials and Structures 9 (1976) 19–32.

[12] H. Asan, Y. S. Sancaktar, Effects of walls thermophysical properties on time lag and decrement factor, Energy and Buildings 28 (1998) 159–166.

[13] H. Asan, Numerical computation of time lags and decrement factores for different building materials, Buildings and Environment 41 (2006) 615–620.

[14] M. M. Vijayalakshmi, E. Natarajan, V. Shanmugasundaram, Thermal behaviour of building wall elements, Journal of Applied Sciences 6 (2006) 3128–3133.

[15] K. J. Kontoleon, D. K. Bikas, The effect of south walls outdoor absorption coefficient on time lag, decrement factor and temperature variations, Energy and Buildings 39 (2007) 1011–1018.

[16] M. Ozel, K. Pihtili, Optimum location and distribution of insulation layers on building walls with various orientations, Building and environment 42 (2007) 3051–3059.

[17] S. A. Al-Sanea, M. F. Zedan, Improving thermal performance of building walls by optimizing insulation layer distribution and thickness for same thermal mass, Applied Energy 88 (2011) 3113–3124.

[18] G. Barrios, G. Huelsz, R. Rechtman, J. Rojas, Wall/roof thermal performance differences between air-conditioned and non air-conditioned rooms, Energy and Buildings 43 (2011) 219–223.

[19] S. A. Al-Sanea, M. F. Zedan, S. N. Al-Hussain, Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential, Applied Energy 89 (2012) 430–442.

[20] M. Ozel, The influence of exterior surface solar absortivity on thermal characteristics and optimum insulation thickness, Building and Environment 39 (2012) 347–355.

[21] C. Balocco, G. Grazzini, A. Cavalera, Transient analysis of an external building cladding, Energy and Buildings 40 (2008) 1273–1277.

[22] P. T. Tsilingiris, Wall heat loss from intermittently conditioned spaces – The dynamic influence of structural and operational parameters, Energy and Buildings 38 (2006) 1022–1031.

[23] ASHRAE, ASHRAE Handbook Fundamentals, SI Edition, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1997.

[24] D. Morillón, Atlas del Bioclima de México, Instituto de Ingeniería, U.N.A.M., México, 2004.

[25] M. A. Humphreys, F. J. Nicol, Outdoor temperature and indoor thermal comfort-raising the precision of the relationship for the 1998 ashrae database files studies, ASHRAE Trans. 106 (2000) 485–492.

[26] Meteotest, Meteonorm, http://www.meteonorm.com (2011).

[27] D. H. C. Chow, G. J. Levermore, New algorithm for generating hourly temperature values using daily maximum, minimum and average values from climate model, Building Serv. Eng. Res. Technol. 28 (2007) 237–248.

[28] J. A. Duffie, W. A. Beckman, Solar engineering of thermal processes, John Wiley and Sons, 1980.

[29] Diario Oficial, Norma Oficial Mexicana NOM-008-ENER-2001, Eficiencia energética en edificaciones, envolvente de edificios no residenciales.

Diario Oficial Miércoles 25 de abril de 2001. Segunda sección, México, p. 59-100. (2001).

[30] B. Givoni, Man, climate and architecture, Applied Science Publishers, London, 1981.

[31] S. V. Patankar, Numerical heat transfer and fluid flow, Taylor & Francis, 1980.

[32] U. S. Department of Energy, Energy Plus V6.0, http://apps1.eere.energy.gov/buildings/energyplus/ (2011).