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ON THE USE OF SUNSPACE AND PCM FOR SPACE HEATING AND COOLING IN GREECE

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ABSTRACT
The present study examines the potential of improving thermal comfort conditions in a single room by means of passive solar systems, natural ventilation and phase change materials. The thermal performances of three different models are investigated on Energy Plus software for the cities of Athens and Thessaloniki, in Greece. To assess the contribution of each model on the thermal conditions of the residence space, a series of thermal comfort indicators were calculated, such as the intensity of thermal discomfort (ITD), the frequency of thermal comfort (FTC) and the fluctuation of discomfort (FD).

INTRODUCTION

The need for energy saving in heating, cooling and ventilation systems of modern buildings is of great importance, as it has been calculated that over 40% of the world's annual greenhouse gas emissions arise from the building sector. The HVAC needs of present constructions thus contribute considerably in the surcharge of atmospheric pollution and the greenhouse effect.

The notions of bioclimatic design, passive solar systems and PCM focus on meeting these needs, by means of using the solar energy and thermodynamic principles, without the interference of mechanical mediums. Passive solar heating has been used extensively throughout history. In 1974, architect David Wright used a large south-facing window as a main passive solar heating strategy in New Mexico [9].Mihalakakou investigated the heating/cooling potential of a sunspace as a function of different climatic conditions in several locations throughout Europe [6], showing that sunspaces can be an appropriate system for winter all over Europe. On the other hand, the use of phase change materials (PCMs) in buildings with the aim of enhancing thermal inertia, thus improving energy performance, is a quite recent research subject.

The objective of this study is to evaluate the thermal performance of the combination of sunspace, Trombe wall, and natural ventilation and PCM technologies for the weather in Greece.

THE CASE STUDY

The Simulated Models

The present case study is consisted of three different models: the first configuration is a simplified model of residence; a single room with a south and north window, in the second model a bioclimatic greenhouse is attached to the south wall of the room and heat is allowed to circulate between the two spaces through a Trombe wall. Finally, at the third model, PCMs are incorporated in part of the sunspace's glazing surface. The sunspace and the room is considered to be two different thermal zones, both naturally ventilated.

The dimensions of the two spaces are shown in Fig.1.The sunspace's height is 3 m on the south wall and 4 m on the connecting wall, giving a 45^{o} gradient on the sunspace roof. Vertical room walls are comprised of four layers: a 15-cm brick layer, expanded polystyrene on the outer side of the wall and one layer of mortar on both sides. The ceiling is made of armed and non-armed concrete, 20 cm and 5 cm thick respectively, expanded polystyrene, mortar and cement mortar. The floor is composed by the same materials as the ceiling with an additional layer of ceramic floor tiles.

Table 1 lists the dimensional and thermal properties for construction elements used in the simulated models. The internal partition between the room and the sunspace is comprised of two layers of mortar and a 12 cm thick brick layer.

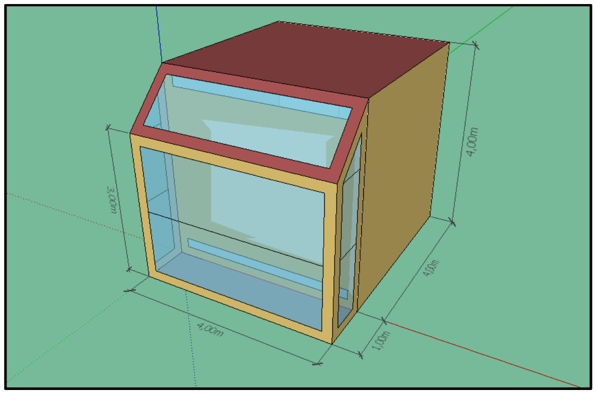

Figure 1: 3D model of the simulated building.

Table 1. Material properties for construction elements

t is thickness, *k* is conductivity, ρ is density and *c* is specific heat.

Materials	t [cm]	k [W/m°C]	ρ [kg/m^3]	c [J/kg°C]
Armed concrete	20	2,5	2400	1000
Mortar	2	0,87	1800	1000
Cement mortar	2	1,4	2000	1100
Brick layer	12	0,51	1500	1000
Expanded polystyrene	3	0,035	23	1450
Wood	1	0,13	500	1600
Ceramic floor tiles	0,5	1,84	2000	840
Polyethylene	0,5	0,33	920	2200

In order for the partition wall to function as a Trombe wall, there are two operable wooden doors 3,6 m x 0,2 m, on the upper and lower part of the wall. The simulations were carried out considering a double pane window for the sunspace and room windows, with a U-value of 5,88 W/°Cm^2. The ratio of the glass surface area to the opaque surface area for the sunspace is equal to 2,06, whereas the room window's dimensions are 0,8 x 0,8 m.

The simulations needed for this study were carried out on Energy Plus version 8.3, for one whole year, by using the weather data of Athens and Thessaloniki. A series of simulations was performed for every site and the parameters that were examined were the construction of the greenhouse roof (glass or opaque) and the melting temperature of the PCM. Products PT25, PT27 and PT29 from Pure Temp were used, which are 100% renewable and have a narrow melting range. Thermo physical properties of the PCM products are cited in Table 2.

Table 2. Thermo physical properties for PCM products

Properties	PT25	PT27	PT29
Melting Point [oC]	25	27	29
Heat of fusion [J/g]	187	202	202
Conductivity (solid) [W/moC]	0,25	0,25	0,25
Denstiy (solid) [g/ml]	0,95	0,95	0,94
Cps [J/goC]	1,99	2,46	1,77
Cpl [J/goC]	2,29	2,63	1,94

Regarding the ventilation of spaces, the type of natural ventilation control in EnergyPlus was chosen to be “Temperature” for external windows and "Adjacent temperature" for Trombe doors. This means that external windows were set to open whenever the zone's air temperature exceeded both a temperature set point T_{set}, defined by the user, and the outdoor air temperature.

The temperature set point T_{set} schedule that was inserted was defined as 3 ^{o}C higher than the optimum indoor temperature T_{comf} (see (6)) for winter months, equal to T_{comf} for mid season and 3 ^{o}C lower than T_{comf} for summertime. Trombe doors would operate by comparing the room's air temperature with the sunspace's air temperature. In the winter and midseasonTrombe doors were scheduled to open when sunspace temperature exceeded the room temperature and vice versa for summertime.

Simulation of the PCM in EnergyPlus

EnergyPlus PCM algorithm uses a one-dimensional conduction finite difference (CondFD) solution algorithm, where the PCM slab is divided into a finite number of nodes and the temporal domain into finite time steps. Tabares-Velasco et al. [8] validated EnergyPlus' PCM model, using an analytical solution from the Stefan Problem, as generalized by Franz Neumann [1], a numerical solution of a sine wave problem through a verified PCM model from Heating 7.3 [2] and experimental data from a hot box apparatus [5]. The CondFD algorithm uses an implicit finite difference scheme, where the user can select between Crack-Nicholson or fully implicit. In the fully implicit scheme, the temperature changes at each node – from a certain time step to the following one – are calculated solely as a function of the temperature of the node at the subsequent time step:

$$C_p \rho \Delta X \frac{T_i^{j+1}-T_i^{j}}{\Delta t} = k_W \frac{T_{i+1}^{j+1}-T_i^{j+1}}{\Delta X} + k_E \frac{T_{i-1}^{j+1}-T_i^{j+1}}{\Delta X}, \quad (1)$$

Where,

$$k_W = \frac{k_{i+1}^{j+1}+k_i^{j+1}}{2},$$

$$k_E = \frac{k_{i-1}^{j+1}+k_i^{j+1}}{2},$$

And k = thermal conductivity, T = temperature, i = node being modeled, $i+1$ = adjacent node to the interior of the construction, $i-1$ = adjacent node to the exterior of the construction, $j+1$ = new time step, j = previous time step, Δt = time step, ΔX = finite difference layer thickness, C_p = specific heat of material and ρ = density of material. As the equivalent specific heat of the PCM is not constant, at each time step its value is updated according to the following equation:

$$C_{eq,i} = \frac{h^{n+1}-h^{n}}{T^{n+1}-T^{n}} \quad (2)$$

The values of the specific enthalpy h for the PCM as a function of the temperature T must be provided by the user. The resulting model is thus a modified version of the enthalpy method. To calculate the needed function of h versus T, as this was not provided by technical datasheets, the effective heat capacity method was used, particularly the triangular function:

$$C_{p,eff} = \begin{cases} C_{ps}, for T \leq T_s \\ 4(H - bC_{ps}) \cdot \left(\frac{T-T_s}{b^2}\right) + C_{ps}, for T_s < T < T_c \\ 4(bC_{pl} - H) \cdot \left(\frac{T-T_s-\frac{b}{2}}{b^2}\right) + 2\frac{H}{b} - C_{pl}, for T_c < T < T_l \\ C_{pl}, for T \geq T_l \end{cases} \quad (3)$$

where, T is PCM's temperature,T_s the solidification temperature, $T_l$the melting temperature, $b = T_s - T_l$ the temperature range of phase change, $T_c=(T_s+T_l)/2$, $C_{ps}$the effective specific heat for solid state, $C_{pl}$the effective specific heat for liquid state and H heat of fusion.

It is important to underline that only one function *h(T)* can be implemented on EnergyPlus, making it impossible to insert the difference between the value of the enthalpy during melting and during solidification process, for a certain temperature *T*, which are known to be unequal due to hysteresis.

In the CondFD algorithm the discretization of space and time is done automatically, using (4):

$$\Delta x = \sqrt{c \cdot \alpha \cdot \Delta t} = \sqrt{\frac{\alpha \cdot \Delta t}{F_o}}, \qquad (4)$$

where c = space discretization constant, α = thermal diffusivity of the material and F_o = Fourier number. The value of c can be selected by the user. Tabares-Velasco et al. [8] demonstrated that EnergyPlus CondFD algorithm is a very reliable model, given that Δt is lower than 4 min and that c = 3 or lower.

Indicators for measuring thermal comfort

In order to quantify the intensity of an uncomfortable sensation in a living space the deviation between the room's operative, and not air, temperature and a thermal comfort temperature range is measured. Evola et al. [3] proposed an indicator called Intensity of Thermal Discomfort for overheating (ITD_{over}) that was defined as the time integral, over the occupancy period *P*, of the positive difference between current operative temperature and the upper threshold for comfort. Hence, ITD_{over} is given by(5):

$$ITD_{over} = \int_P \Delta T^+(t)dt \qquad (5),$$

$$\text{Where} \quad \Delta T^+(t) = \begin{Bmatrix} T_{op}(t) - T_{lim}, if T_{op}(t) \geq T_{lim} \\ 0, if T_{op}(t) < T_{lim} \end{Bmatrix}$$

In this study the indicator ITD was used also for wintertime, proposing ITD_{below}, which is defined as the time integral, over the occupancy period P, of the positive difference between the lower threshold for comfort and current operative.

The values of thermal comfort upper and lower limits depend on the choice of the thermal comfort model. In this paper, the Adaptive Comfort Standard (ACS) of ASHRAE Standard 55 is chosen, which implies that the temperature limits are not constant in time, but are determined monthly as a function of the running mean outdoor air dry bulb temperature $T_{a,out}$. The ACS was specifically developed for naturally ventilated buildings and calculates the optimum comfort temperature T_{comf} as:

$$T_{comf} = 0{,}31 \cdot T_{a,out} + 17{,}38,$$
$$for 10°C \leq T_{a,out} \leq 33°C. \qquad (6)$$

For $T_{a,out}$ that exceed the above limits, the comfort range values were considered constant, as proposed by Ghiaus et al. in [4].The range of temperatures around T_{comf} that corresponded with 90% and 80% of thermal acceptability were specified as a variance of 2,5 and 3,5Crespectively.

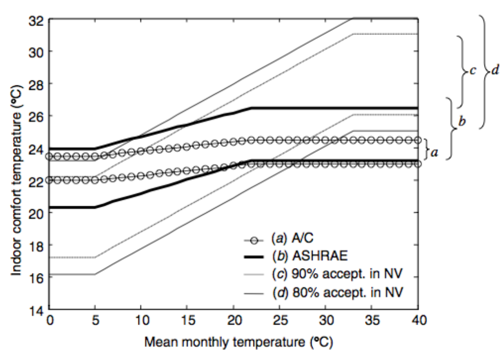

Figure 2: Comfort range for air conditioning and natural ventilation: (a) air conditioning, (b) ASHRAE comfort range, (c) N/V, 90% acceptability limits, (d) N/V, 80% acceptability limits. [4]

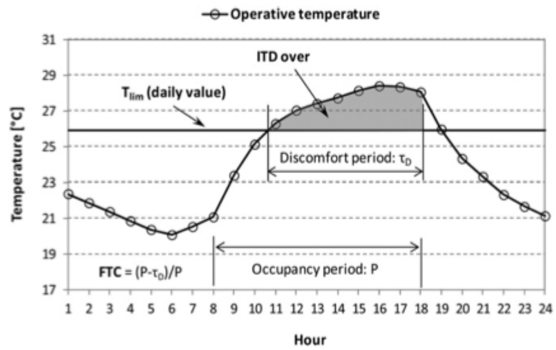

Figure 3: Intensity of thermal discomfort (ITD_{over}) and frequency of thermal comfort (FTC): graphic definition. [3]

In Ref. [3] Evola et al. introduced another indicator, called the Frequency of Thermal Comfort (FTC), which is defined as the percentage of time, within a given period *P*, during which the indoor thermal conditions are met, see (7) and Fig. 3.

$$FTC = \frac{P - \tau_D}{P}. \qquad (7)$$

In Ref. [7], Siccurela et al. proposed one more indicator called Fluctuation of Thermal Discomfort, FD, and defined as the ratio of the ITDto the length of the period when thermal discomfort is actually perceived, τ_D.

$$FD = \frac{ITD}{\tau_D}. \qquad (8)$$

RESULTS AND CONCLUSIONS

The results of the simulations that are reported in this paragraph concern the optimum model for each configuration and city. Thus, in Athens the sunspace functioned better with an opaque roof, as a glass roof developed extreme overheating in summer, and the best performing PCM was PT29, which was added on the lower half of the vertical glazing. In Thessaloniki window roof for the greenhouse was preferable and PT27 functioned better than the other PCMs when incorporated at the greenhouse ceiling. When assessing the performance of a system for improving indoor thermal conditions, one usually looks at the zone air temperature profile for a representative period of time. In accordance with this approach, the case study of two months, January and August are reported in Figs. 4 and 5, for the three models of simulation: room, sunspace and sunspace with PCM, for Athens and Thessaloniki.

In particular, Figs. 4 and 5 illustrate the evolution of the room's operative temperature, instead of the zone's air temperature, as it is the operative temperature that directly affects the comfort sensation, according to well established comfort theories. As shown by Figs. 4a and 5a, the installation of a sunspace, with or without PCM, can result in both lower and higher zone temperatures during wintertime for both cities, which can be attributed to fluctuations in solar radiation. In the case of a cloudy day, the sunspace is not able to raise its' interior temperature, and combined with the fact of higher thermal losses by the windows when compared to the plain room's insulated envelope, results in reduced operative temperatures.

Another phenomenon that appears in these diagrams is the fact that whereas PCM establish an increased mean operative temperature in the Athenian model during winter, in Thessaloniki the sunspace without PCM appears to be the preferable scenario. Regarding Figs. 4b and 5b, it is obvious that the attachment of a sunspace intensifies thermal discomfort in the chosen cities, due to overheating.

One can also observe that PCM are a positive attachment for summer conditions in both cities, as they yield lower temperatures in the room compared to the simple sunspace model, with the temperature reduction being amplified for the city of Thessaloniki. However, the results shown above concern a relatively small period of time and are not suitable for an effective comparison throughout a whole year.

Therefore, the indicators mentioned above were calculated. The annual ITD, as the sum of ITD_{below} and ITD_{over}, is reported in Fig. 6.A deeper analysis on the nature of thermal discomfort, whether it is from overheating or cold, is illustrated in Fig. 7, where it is shown that the initial model did not develop any overheating in either location. On the contrary, sunspaces reveal an overheating problem but manage to balance this in the values of annual ITD, due to the greenhouse's positive effect in winter.

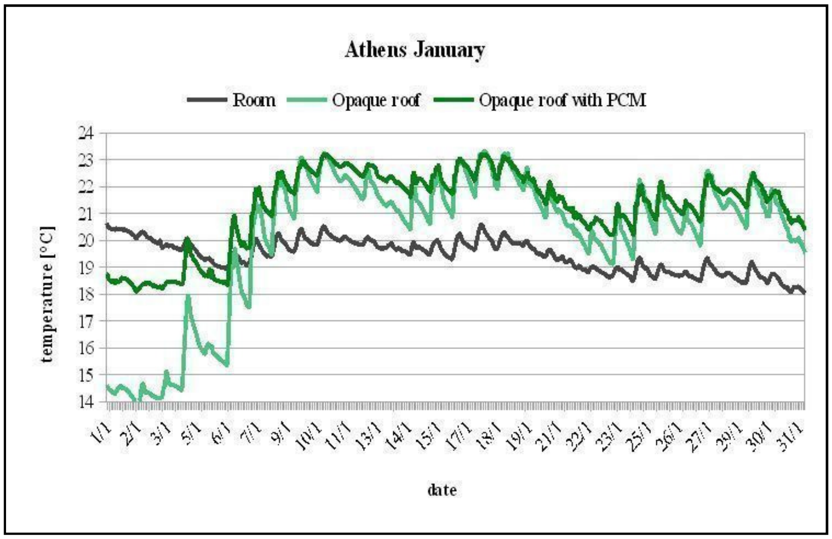

Figure 4a:Athens zone operative temperatures for January

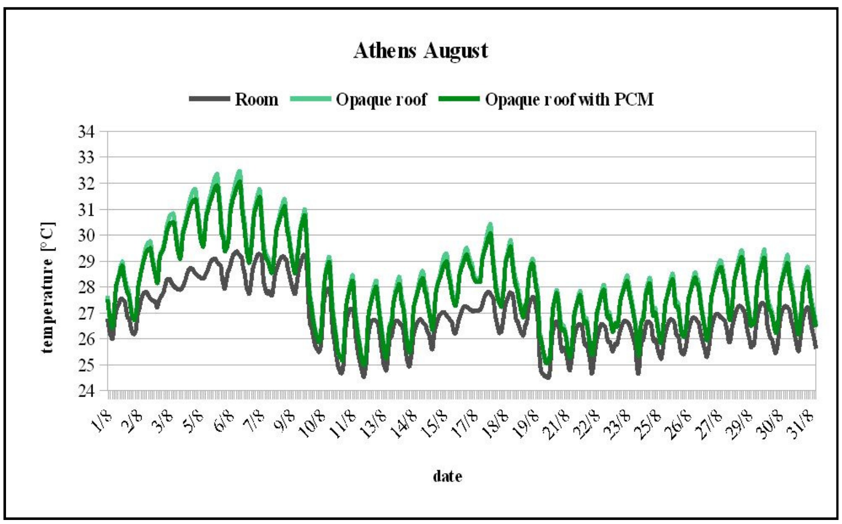

Figure 4b:Athens zone operative temperatures for August

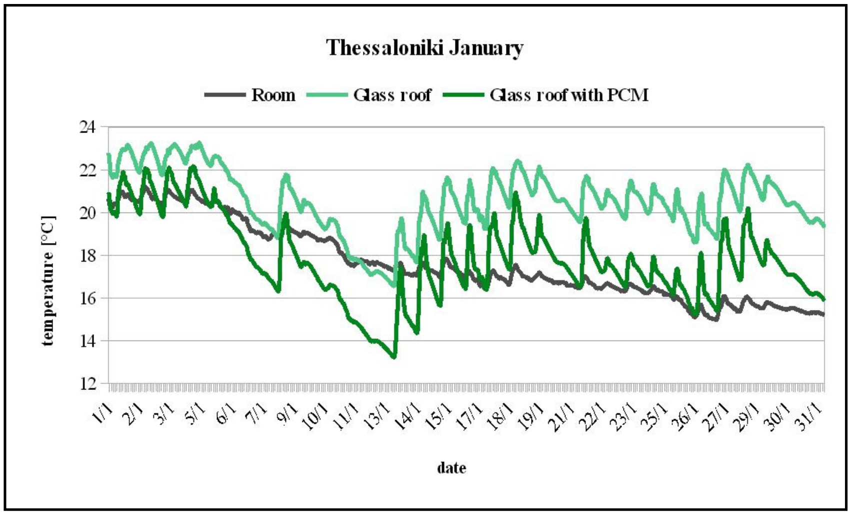

Figure 5a: Thessaloniki zone operative temperatures for January

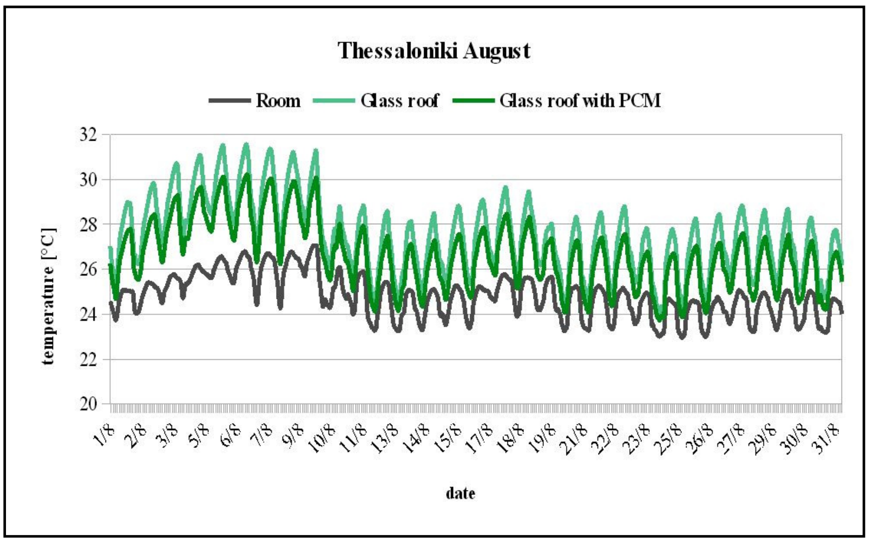

Figure 5b: Thessaloniki zone operative temperatures for August

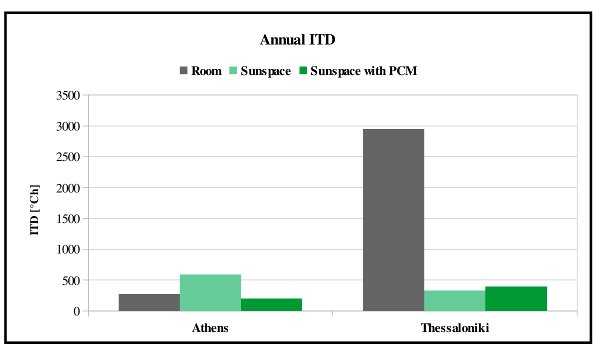

Figure 6: Annual ITD for all configurations

Another fact worth mentioning is the increase of ITD_{below} between room and sunspace scenario in Athens. All of the thermal comfort indicators are reported in Table 3.

Table 3. Values of thermal comfort indicators for all models

	Configuration	annual ITD [°Ch]	τ_D [h]	FTC [%]	FD_{below} [°C]	FD_{over} [°C]
Athens	**Room**	275,32	611	93,03	0,45	0,00
	Sunspace	583,86	612	93,01	1,86	0,78
	Sunspace with PCM	203,16	278	96,83	0,00	0,73
Thessaloniki	**Room**	2944,19	2316	73,56	1,27	0,00
	Sunspace	333,23	450	94,86	0,37	0,82
	Sunspace with PCM	391,26	435	95,03	1,03	0,52

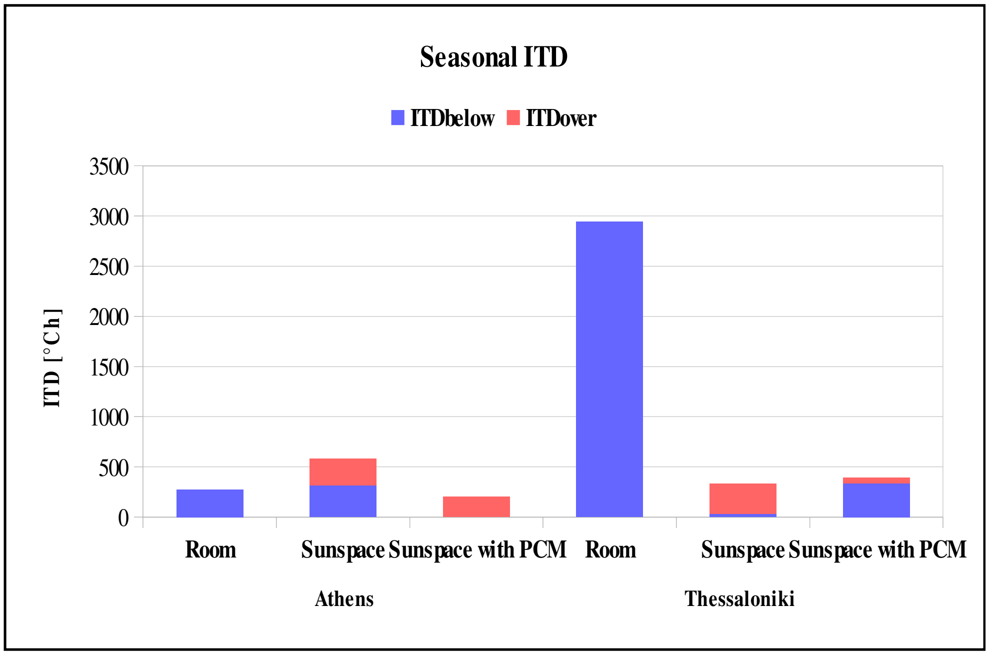

Figure 7: Seasonal ITD for all configurations

From Table 3we can derive the following assumptions:

- The best performing configuration, in terms of annual ITD, is sunspace with PCM PT29 for Athens and sunspace alone for Thessaloniki, with a slight difference of 58 °Ch less than the PCM model.
- The optimum model for Athens yields a 26,21% reduction of the total ITD, whereas the best configuration for Thessaloniki establishes an explicit reduction of 88,68% of the initial annual ITD value.
- The model with the minimum discomfort period τ_D was the greenhouse with PCM for both locations. For this reason, the same models appeared to have the maximum frequency of thermal comfort FTC.
- The fluctuation of discomfort FD in Athens is minimum for the basic model of a simple room, while in Thessaloniki FD_{under} and FD_{over} for the PCM model are both lower than FD_{under} in the simple room.

By the values of ITD_{below} and ITD_{over} we comprehend that in Athens the version of a sunspace with opaque roof might be preferable for the summer, due to the fact of smaller overheating effect, but in wintertime the opaque roof does not let enough radiation enter the greenhouse and the amount of heat that is transferred to the room via the connecting Trombe wall is inadequate. PCM on the other hand, when added to the vertical windows of the sunspace are able to store enough of solar radiation energy and retransmit it towards the inside of the greenhouse, minimizing uncomforted conditions through winter. In Thessaloniki, where outdoor air temperatures are lower than in Athens, PCM don't manage to withhold the heat energy they have gathered through the day and mainly transmit it to the outdoor environment, making the sunspace without phase change materials the optimum scenario.

By the above, we realize that the incorporation of PCM is not an a priori positive addition and all the incorporation parameters should be examined carefully before the implementation.

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