OPTIMIZING INSULATION-THERMAL MASS WALL LAYER DISTRIBUTION FROM MAXIMUM TIME LAG AND MINIMUM DECREMENT FACTOR POINT OF VIEW

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ABSTRACT

Different wall construction configurations lead to different wall thermal behaviour which affects energy consumption and thermal comfort of the room. In this study, the thermal time constant, the time lag, and the decrement factor are calculated for different wall configurations in order to investigate the best insulation/thermal mass layer distribution in external walls. First, this is done for just a wall by developing a numerical model to solve the one dimensional heat transfer equation in a multilayered wall subjected to convective boundary conditions. Second, this is done for a full-scale house using the whole building energy simulation program EnergyPlus. Also, the performance of traditional insulation is compared to that of a newly developed insulating coating, based on super-insulating silica aerogels, from maximum time lag and minimum decrement factor point of view. Results showed that placing a layer of insulation at the middle of the wall and another one at the outer wall surface or using a five layered wall: 1- three layers of insulation placed at the inside, middle, and outside and 2- three layers of thermal mass separated by two layers of insulation are the best configurations. Also, the insulating coating showed a better performance with an increase in time lag of about 1 hour and decrease in decrement factor of about 5%.

INTRODUCTION

In France, the building sector accounts for about 43% of the total energy use and 25% of carbon dioxide emissions[1]. France has already adopted the objective of reducing its energy consumption and greenhouse gas emissions by a factor of four to five by the year 2050 as a part of its national strategy for sustainable development, introduced in June 2003, and it's Climate Plan, introduced in July 2004. The new thermal regulations (RT 2012) limits the primary energy consumption for new buildings to 50 kWh/m2 per year (this includes heating, cooling, lighting, water heating, and ventilation), and also requires a better thermal comfort through limiting overheating during summer season; thus, it is crucial to find solutions to reduce energy consumption and enhance thermal comfort. Super-insulating materials, such as silica aerogels and vacuum insulation are one of the promising techniques to be used in building envelopes to obtain the desired objectives.

Energy consumption reduction is not our only concern. Occupants' thermal comfort is also a major issue to be considered and optimized. Thermal insulation decreases the heating load in winter; however, it may lead to overheating in the summer period. Also, the position and distribution of thermal insulation will affect the dynamic thermal performance of the building's envelope and interior environment. Thermal inertia of the building has a great influence on the indoor environment. A massive layer near the inside space can absorb the day heat energy and release it in a later time of the day. This energy absorption dampens the daily outside temperature fluctuations and decreases the peak load of the space. Insulation, due to its low thermal capacitance, responds rapidly to any change of the outside driving forces making it a good solution for short periods and intermittent air-conditioning. These phenomena are related to important parameters: thermal time constant, time lag, and decrement factor. The time required for heat wave to propagate through a wall from the outside to the inside is defined as the time lag. The decreasing ratio of its amplitude during this process is called the decrement factor.

Tsilingiris [2] developed a numerical simulation model to estimate the thermal time constant for several wall structures. It was shown that as thickness of the massive layers increase the thermal time constant increases. For the same thickness of concrete layers, as the insulation layer is moved from outer wall surface to the inner one, the time constant decreases. Asan [3-5] estimated the time lags and decrement factor for different building materials by solving the one-dimensional heat transfer equation numerically using Crank-Nickolson scheme, and

imposing a periodic boundary condition at the outside environment. Three groups of materials were used. The first has low thermal conductivity and low heat capacity, the second has high thermal conductivity and high thermal mass, and the third has moderate thermal conductivity and high thermal capacity. Kontoleon et. al. [6] investigated the influence of wall orientation and solar absorptivity on time lag and decrement factor for the cooling season in Greece for several insulated wall configurations. Kaska and Yumrutas [7, 8] calculated time lag and decrement factor values for eight types of walls and two types of flat roofs using an experimental set up. Ulgen [9] investigated the effects of a wall's thermo-physical properties on time lag and decrement factor both experimentally and theoretically. Sun et al. [10] scrutinized experimentally and numerically how these two parameters are influenced by the outside temperature.

Within the Parex.it project, an innovative insulating coating based on super-insulating materials silica aerogels has been developed (Fig. 1) possessing a very low thermal conductivity relative to other available coatings. Its thermal conductivity, density, and specific heat are 0.035 W/(m.K), 300 J/(kg.K), and 1100 kg/m^3, respectively.



Fig. 1: The innovative insulating coating

Adding this coating to the building facades will decrease the energy load of the space; also, it will change the thermal behavior of the whole structure. A first objective of this study is to know the best wall configuration of thermal resistive and capacitive layers through determining the thermal time constant, the time lag, and the decrement factor (all these terms are defined in the next section). All these configurations have the same total R-value; however, the outside to inside layers of the wall are different. The best configuration is the one that ensures a minimum decrement factor and maximum time lag. A second objective is to compare the performance of traditional insulation with that of Parex.it coating from maximum time lag and minimum decrement factor point of view.

WALL THERMAL TIME CONSTANT, TIME LAG, AND DECREMENT FACTOR

Thermal Time Constant

Thermal time constant is derived from its notion in physics. It is the time taken by an output response signal to reach 63% of its steady state value due to a step change in the input signal.

Consider a wall separating the indoor and outdoor environments. If the outdoor and indoor air temperatures are kept constant, the system will reach a steady state where the temperatures through the wall will change no more. Any step temperature change of the outside air temperature causes a transient change in the wall temperatures till reaching new steady state values.

Owing to a step change in the outdoor air temperature, the developed transient inside wall surface temperature decreases or increases exponentially till reaching steady state, this can be expressed in equation (1),

$$\begin{cases} T(\mathrm{L,t}) = T_{ss} + (T(L,0) - T_{ss})e^{-t/\tau} \\ \text{if } T(\mathrm{L,t}) \text{ is decreasing with time} \end{cases} , \quad (1\text{-a})$$

$$\begin{cases} T(\mathrm{L,t}) = T_{ss} - (T_{ss} - T(L,0))e^{-t/\tau} \\ \text{if } T(\mathrm{L,t}) \text{ is increasing with time} \end{cases} , \quad (1\text{-b})$$

where $T(L,t)$, $T(L,0), T_{ss}, t$ and τ are the inner wall surface temperature at any time t, the initial inner wall surface temperature at time to, the steady state value, time, and the time constant respectively.

For t = τ, we have:

$$\begin{cases} T(L,\tau) = T_{ss} + (T(L,0) - T_{ss})e^{-1} \\ \text{if } T(L,\tau) \text{ is decreasing with time} \end{cases} , \quad (2\text{-a})$$

$$\begin{cases} T(L,\tau) = T_{ss} - (T_{ss} - T(L,0))e^{-1} \\ \text{if } T(L,\tau) \text{ is increasing with time} \end{cases} , \quad (2\text{-b})$$

When the solution of T is obtained, we can find the time constant using equation (2).

Time lag and decrement factor

As illustrated in Figure 2, time lag is the time it takes for the heat wave to propagate from the outer surface to the inner surface of the wall and the decrement factor is the decreasing ratio of its amplitude. These are calculated as follows:

$$\text{time lag}, \emptyset = t_{in,max} - t_{out,max} \quad (3)$$

$$dec\ factor, f = \frac{A_1}{A_2} = \frac{T_{in,max} - T_{in,min}}{T_{out,max} - T_{out,min}} \quad (4)$$

where $t_{in,max}$ and $t_{out,max}$ represent the time in hours when inside and outside surface temperatures are at their maximums, respectively; $T_{in,max}$,$T_{in,min}$,$T_{out,max}$ and $T_{out,min}$ are the maximum and minimum inner wall surface temperatures and maximum and minimum outer wall surface temperatures, respectively.

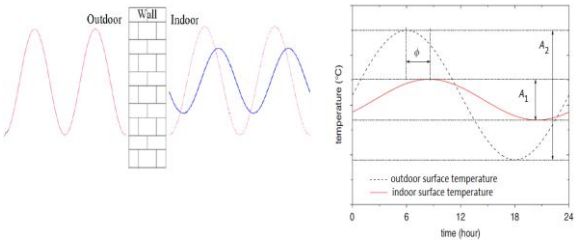


Fig. 2: Time lag and decrement factor

METHODOLOGY

First the time constant, time lag, and decrement factor will be calculated for just a wall using a wall model developed in MATLAB® [11] and second these will be calculated for a house using EnergyPlus [12], a whole building energy simulation program.

Study on a Wall

The transient one-dimensional heat conduction equation in a multilayered wall consisting of N parallel layers (Fig. 3) is given by equation (5):

$$\rho_i c_i \frac{\partial T_i(t,x)}{\partial t} = k_i \frac{\partial^2 T_i(t,x)}{\partial x^2} \quad (5)$$

where: i represents the ith layer within the wall, t and x are the time and spacial coordinates, T_i is the temperature, k, ρ, and c are the thermal conductivity, density, and thermal capacity respectively.

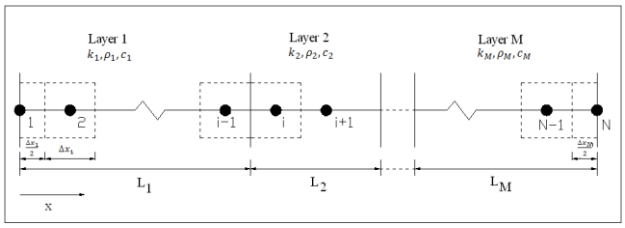


Fig. 3: Discretised multi-layer wall

The boundary conditions at the outdoor and indoor surfaces of wall are:

$$h_{c\infty}[T_\infty(t) - T(0,t)] = -k\frac{\partial T(0,t)}{\partial x} \quad (6)$$

$$h_{ca}[T(L,t) - T_a(t)] = -k\frac{\partial T(L,t)}{\partial x} \quad (7)$$

where $h_{c\infty}$ *and* h_{ca} are the convective heat transfer coefficients at the outdoor surface and the indoor surface of wall, respectively.

$T_\infty(t), T(0,t), T_a(t)$ *, and* $T(L,t)$ are the ambient air, outside wall surface temperature, room air, and inner wall surface temperature respectively.

The outside air temperature is assumed to vary as a sinusoidal function during a 24-h period and is calculated using equation (8):

$$T_\infty = \frac{T_{\infty,max} - T_{\infty,min}}{2}\sin\left(\frac{2\pi t}{P} - \frac{\pi}{2}\right) + \frac{T_{\infty,max} + T_{\infty,min}}{2} \quad (8)$$

where P is the period, $T_{\infty,max}$ and $T_{\infty,min}$ are the maximum and minimum outdoor air temperatures, respectively.

Numerical Solution:
The solution of the one-dimensional heat conduction equation (5) is derived numerically using the implicit finite volume method. The code is developed using MATLAB®. The composite wall of M layers is discretized into a number of nodes. The result is a set of linear algebraic equations which can be written in a matrix form,

$$A * T = b \quad (9)$$

where A is a tri-diagonal highly sparse matrix.

The matrix function " \ " (mldivide) in MATLAB® is used to solve the above equation. A time step of 1 min is considered. Starting from an arbitrary chosen initial values for the wall temperatures, the daily cycle of the outside environmental conditions is repeated on several consecutive days until a steady periodic solution is obtained during which quasi steady-state solutions are developed.

Study on a whole Building

Time lag and decrement factor are now calculated for a full-scale house using the whole building energy simulation program EnergyPlus. Figure 4 shows the geometry of the house which represents a typical French house. The south wall has the largest glazing area of 32% of the total opaque area; the west, east

and north glazed areas are 13%, 4.5%, and 3% respectively.

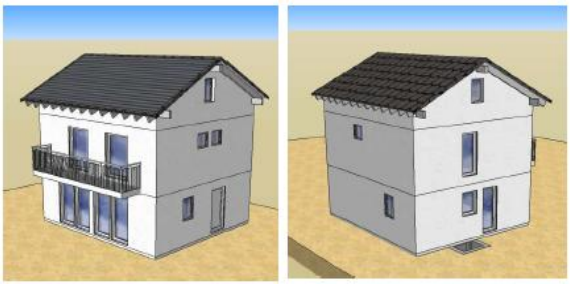


Fig. 4: Full-scale house case study

WALL CONFIGURATIONS

Table 1 shows the 8 different wall configurations being studied. All the wall structures considered in this study have the same total R-value; so, what changes are the number and thickness of insulation and thermal mass layers as well as the position of insulation within the wall. For example, in case 1, we have 5 cm thermal insulation placed at the outer wall surface; however, in case 2, it is placed at the inner side. Case 3 has 2 insulation layers one at the outside and one at the inside; for the total R-value to be kept constant, each of these insulation layers has thickness of 2.5cm.

Table 1: Wall layer configurations

case	outside layer	layer 2	layer 3	layer 4	layer 5
1	insulation	mass			
2	mass	insulation			
3	insulation	mass	insulation		
4	mass	insulation	mass		
5	insulation	mass	insulation	mass	
6	mass	insulation	mass	insulation	
7	insulation	mass	insulation	mass	insulation
8	mass	insulation	mass	insulation	mass

RESULTS

Wall Model

The wall being studied consists of thermal resistive and capacitive layers. The resistive layer could be traditional insulation or Parex.it coating and the capacitive layer is concrete. Table 2 shows the characteristics of these materials.

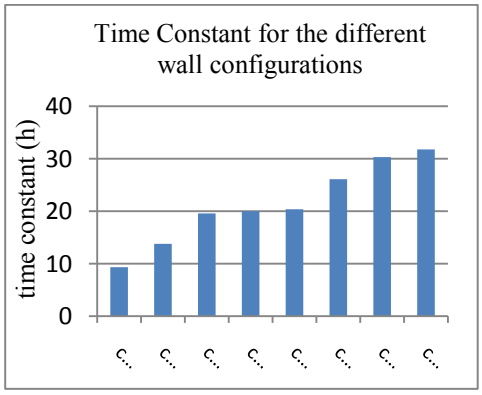
Table 2: Thermal characteristics of the different materials used

	insulation	concrete	Coating
Thermal conductivity (W/m.K)	0.044	2	0.035
Density (kg/m3)	12	2000	300
Specific heat (J/kg K)	840	1000	1100

To calculate the wall thermal time constant, the indoor air temperature is kept constant at 20°C; however, the outdoor air temperature undergoes a step change in temperature. This gives rise to a transient behavior of the inner wall surface temperature until reaching steady state. Plotting this latter would allow us to determine the time constant.

Figure 5 shows the time constant for the different wall structures. We find that the best configuration that results in maximum wall thermal time constant is the one having two insulation layers placed at the inner and outer wall surfaces, followed by the case where three insulation layers are placed one at the inner surface, one at the outer surface, and one at the middle of the wall separated by two capacitive layers. The worst among all is the one where insulation is placed as one layer at the inside surface of the wall.

Comparing case 1 (outside insulation – thermal mass) with case 2 (thermal mass – inside insulation), we see that placing a massive layer near the indoor environment leads to larger time constant; 19.55 for case 1 while 9.33 for case 2. This illustrates the effect of heat storage near the indoors which delays the outside heat wave to propagate towards the inside space.



case	Layers (outside -----> inside)
1	R-C
2	C-R
3	R-C-R
4	C-R-C
5	R-C-R-C
6	C-R-C-R
7	R-C-R-C-R
8	C-R-C-R-C

R = Insulation
C = Thermal mass

Fig. 5: Time Constant for the different wall configurations

Figure 6 shows the variation of the inside wall surface temperature for the different cases after the outside air temperature undergoes a step change from 10°C to 0°C.

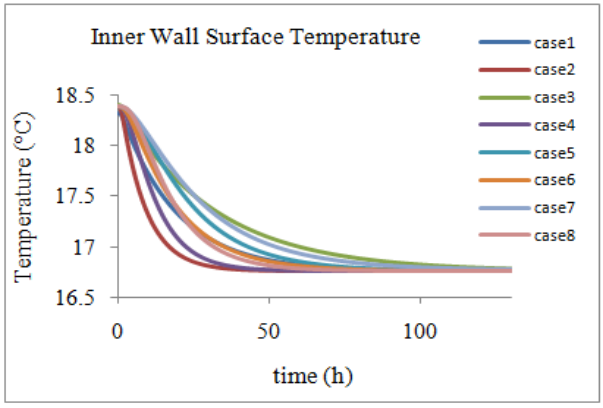


Fig. 6: inside wall surface temperature for the different cases

Now, instead of using the traditional insulation, we will use Parex.it coating. Figure 6 compares the time constant for the different wall configurations when using traditional thermal insulation with that when using Parex.it coating. Note that for the wall R-value to be kept constant, the thickness of Parex.it coating is altered so the thermal resistance of the insulation will be equal to that of the coating; thus, instead of 5 cm insulation, we use 5.68 cm coating.

The results of figure 7 show that Parex.it coating performs better for all the cases with an increase in the time constant of about 1.5 hours. This is due to the higher thermal capacitance found in the coating.

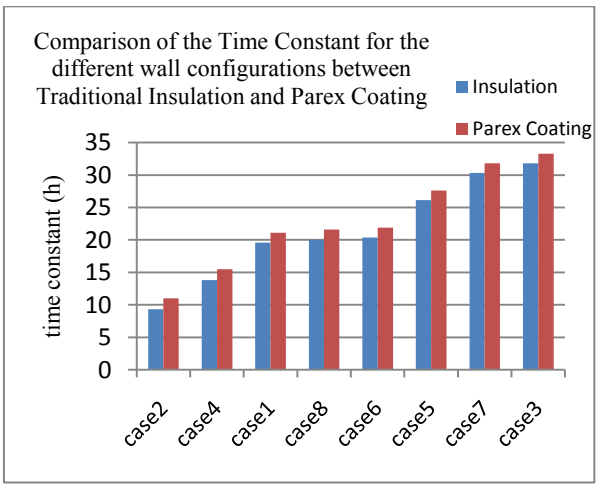


Fig. 7: Comparison of the Time Constant for traditional Insulation and Parex.it Coating

To calculate the time lag ∅ and decrement factor *f*, the outside air temperature is allowed to vary as a sinusoidal function throughout the day using equation (8), where $T_{\infty,max}$, $T_{\infty,min}$, and P are taken as 10, 0, and 24 respectively. The indoor air temperature is kept constant at 20°C. Figure 8 shows a plot of ∅ and f for the different wall configuration cases when using traditional insulation.

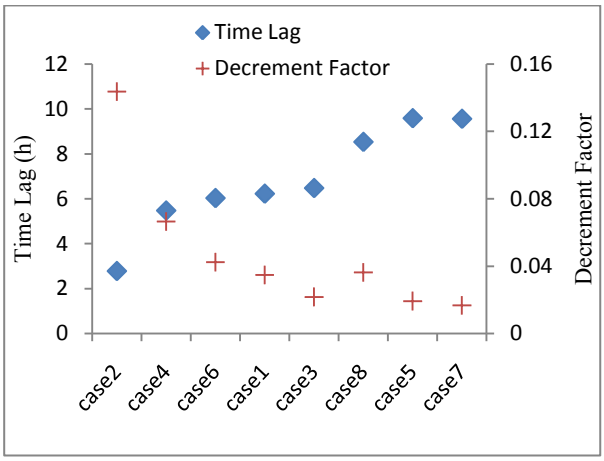


Fig. 8: Time lag and decrement factor for the different wall configuration cases

The best wall structure is the one that has maximum time lag and minimum decrement factor. Of all, cases 5 and 7 (RCRCR) give this result. So placing three insulation layers, one at the inside surface, one at the outside surface, and one at the middle or placing two insulation layers one at the outer surface and one at the middle has the best performance. Case 8 (CRCRC) also gives a very good performance. The worst of all is the case where insulation is placed at the inner wall surface.

The inner wall surface temperature is plotted for cases: "1" (insulation is placed outside), "2" (insulation is placed inside), and "3" (insulation is placed inside and outside) (Fig. 9). This figure shows how the peak temperature is lower for the case where insulation is outside and is also more delayed. Furthermore, the fluctuation in the temperatures throughout the day is decreased which has a positive effect on thermal comfort. Splitting the insulation layer into two and placing one at the inside and one at the outside (case 3) will also improve the performance.

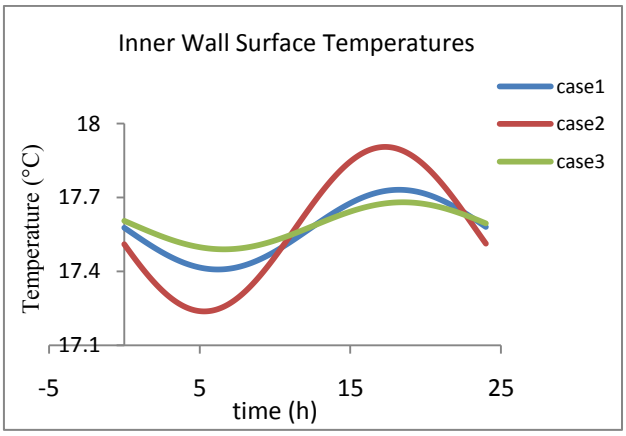


Fig. 9: Comparison of inner wall surface temperature profiles between cases 1, 2, and 3

The time lag and decrement factor are recalculated for all the different cases but at this time replacing traditional insulation with Parex.it coating. We can illustrate from Figure 10 that Parex.it coating has a better performance for all the cases from maximum time lag and minimum decrement factor point of view with an increase in time lag of about 1 hour and decrease in decrement factor of about 5%.

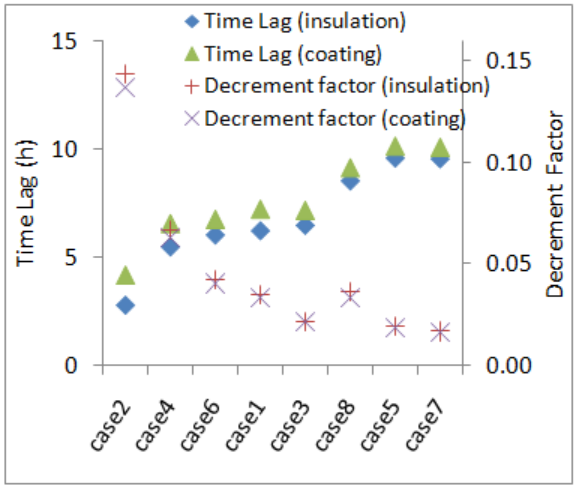


Fig. 10: Time lag and decrement factor when using Parex coating and traditional insulation

Whole Building Model

In the previous section, we found the best layer configuration using just a wall model. In this section, the same study is done but on a full-scale house using the whole building energy simulation program EnergPlus. Figure 11 shows the time lag and decrement factor for the different wall structures when using traditional insulation. We can see that cases 5, 7, and 8 have the best performance from a maximum time lag and minimum decrement factor point of view. Case 5 has the minimum decrement factor however case 8 has the maximum time lag.

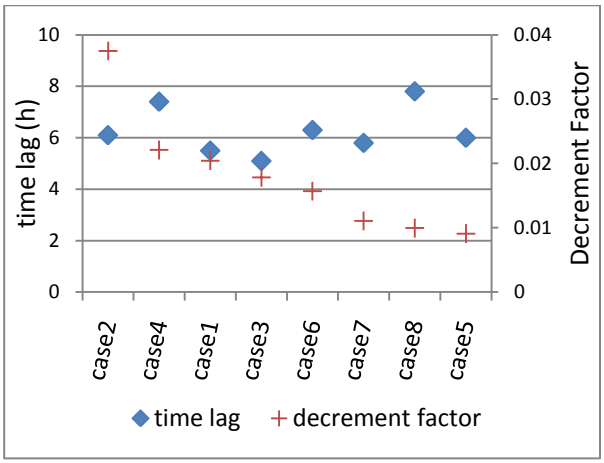


Fig. 11: time lag and decrement factor for the different cases (full scale house)

These best cases are the same obtained with the study on the wall only. Thus, placing a layer of insulation between two capacitive layers and another one at the outer wall surface (RCRC configuration) or using a five layered wall: 1- three layers of insulation placed at the inside, middle, and outside (RCRCR) or 2- three layers of thermal mass separated by two layers of insulation (CRCRC) give the best results. Replacing traditional insulation with Parex.it coating, time lag and decrement factor are plotted in figure 12 for all the different case. Also, we conclude that the coating has a better performance.

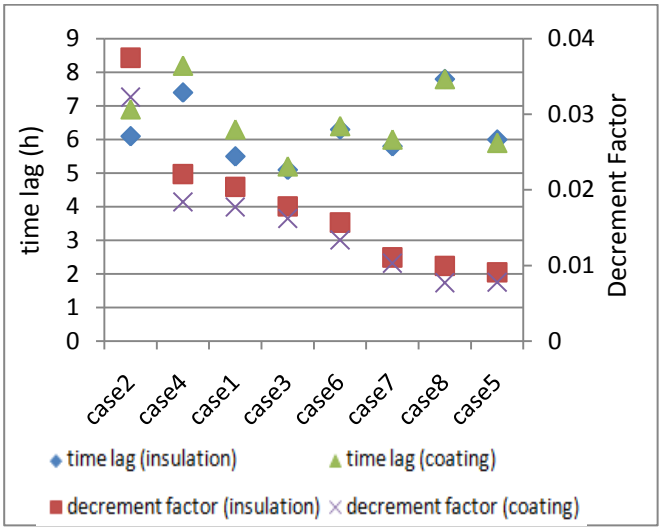


Fig. 12: Comparison of time lag and decrement between insulation and coating cases

CONCLUSION

In this study, we calculated the time lag and decrement factor for different multilayered wall configurations consisting of insulation and thermal mass layers. All these wall configurations have the same total thermal resistance; however, the number and position of thermal insulation differ. Then, the same study was done but replacing traditional insulation with Parex.it coating. Results showed that a '4' layered structure: layer of insulation between two capacitive layers and another one at the outer wall surface or '5' layered wall: 1- three layers of insulation placed at the inside, middle, and outside or 2- three layers of thermal mass separated by two layers of insulation give the best results. Also, Parex.it coating showed a better performance than traditional insulation from maximum time lag and decrement factor.

NOMENCLATURE

$\emptyset$: time lag (s)
f: decrement factor
T: temperature (K)
ρ: density (kg/m3)
c: specific heat (J/kg.K)
k: thermal conductivity (W/m.K)
x: special coordinate (m)
t: time (s)
k: thermal conductivity (W/m.K)
τ: thermal time constant (s)
L: wall length (m)
h: heat transfer coefficient (W/m .K)

subscripts
∞: outdoor
a : indoor
ss: steady state

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