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The Effect of Roof Heat Capacity on Heat Gain in Different External Conditions

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Abstract: *In this study, thermal performance of four kinds of roofs with different heat capacity in different external conditions is investigated by numerical simulation using EnergyPlus software. Four roofs which their thermal capacity varies from 167 to 712 kJ/m^{2}K are studied. In addition to the heat transfer rates, the time lags and decrement factors are evaluated to compare the roofs' performance. The result of this study indicates that increasing the heat capacity of the roof leads to a decrease in the difference between its maximum and minimum loads and decrement factor and also increase in the time lags especially in the dry climate and high-radiation condition. However, the total load reduces slightly only in the high-radiation condition. Also, the external conditions have no significant effect on the decrement factor. Finally, increasing the thermal capacity and solar shading of the roof would be appropriate passive strategies for reducing the energy usage in buildings.*

Keywords: *Roofing materials; Thermal capacity; Heat gain; Cooling load; Time lags.*

Introduction

Approximately 25-30 percent of the world's energy is consumed in buildings. Nearly 80 percent of this energy is used for cooling and heating of space in commercial and residential buildings (Yesilata et al. 2011). To reduce energy consumption and the cost of energy, energy efficiency in buildings should be improved by enhancing the building construction systems and using new technologies (Martins et al. 2016).

The most important goal in the air conditioning of buildings is to create comfort and control the temperature of a given space. In summer, external conditions like solar radiation and outside air temperature and internal parameters such as latent and sensible loads of equipment and people's activities have major effects on the indoor air temperature. Due to these factors, peak load usually occurs around noon or in the first hours of the afternoon. To decrease the energy consumption of air conditioning systems, it would be beneficial to take actions to reduce the amplitude of the peak load and to shift peak hours to a later time in a day (Balaras 1996). One way is optimal design and construction of buildings. Suitable design helps to create comfortable conditions and also helps to decrease energy for cooling and heating of spaces (Maneewan et al 2004).

Also, there are many effective design parameters which should be considered to have an appropriate indoor condition and better energy consumption in buildings. These factors are the site and the building's situation and form, the distance between buildings, and physical properties of materials used in the building envelope. Among these parameters, the building elements such as walls and roofs which are exposed to external conditions are the most important factors (Yilmaz 2007).

In recent years, analyses of thermal properties of building elements to study their thermal performance have become more common. Investigations in this field on the one hand help to decrease energy consumption in buildings by choosing components with more appropriate thermal properties. On the other hand, they help to reduce the size of air conditioning systems while comfortable indoor temperatures are provided for residents (Han et al. 2009).

As a building element, the roof is influenced most by external climatological parameters and approximately half of the cooling load of a one or two story building is received through the roof in arid areas (Runsheng et al. 2003). Also, roofs had a major portion in total heat gain in Indian concrete buildings during the tropical summer which ranged from 40 to75% (Vijyakumar et al. 2007).

On the other hand, the roof is considered as one of the most important part of buildings when the passive strategy is considered for buildings. For instance, shading the roof, increasing the roof thickness and surface reflectivity, optimizing the thermal insulation thickness, using vegetated roofs and roof ponds are the main passive strategies which have been considered in recent studies (Sharifi et al. 2015). Daouas (2017) in his study analyzed the influence of external long-wave radiation on the optimum thermal insulation thickness of roofs in Tunisian buildings. The study concluded that the long wave radiation has major effect on the annual heat gain and

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optimum thickness of insulation. Also, in another study the effect of surface color on the optimum thermal insulation thickness of residential buildings have been evaluated in different climates in China which experienced hot summers (Yu et al. 2011).

Although the previous studies mainly focused on the reduction of cooling load by implementing passive strategies such as cool roofs, vegetated roofs, and optimization of thermal insulation, the effects of thermal capacity on the cooling load reduction in arid and humid climates has not been sufficiently investigated. One possible way of research could be managing the thermal capacity instead of adding extra thermal insulation to control total heat gain and peak load in buildings.

Different numerical methods and simulation tools are used to analyze the thermal performance of roofs and walls in different conditions. Many researchers have studied the heat transfer through walls and roofs with time-periodic boundary conditions by considering air-conditioned space (Barrios et al. 2012; Mackey and Wright 1946; Chen and Krokosky 1976; Al-Regib and Zubair 1995; Al-Sanea 2002). In these studies, a wide range of methods is used to analyze one dimensional heat transfer in monolayer and multilayer roofs and walls. In the studies above, material properties and convective heat transfer coefficient of indoor and outdoor have been assumed constant. They showed that the amplitude of heat wave that travels from the outer surface to the inner surface depends on the solar radiation and convection between the outer surface and ambient air as Asan (2006) mentioned. Moreover, researche showed that the decrease of the amplitude of heat wave depends on the envelopes' thickness and their composition (Asan 2006; Larsen et al. 2009; Athanssoulis and Massouros 1999; Asan and Sancaktar 1998; Asan 2000; Kontoleon and Eumorfopoulos 2008). Also, this conclusion validates that the amplitudes of these heat waves decrease when they reach the inner surface. In most studies, two important parameters are used, i.e., decrement factor and time lags to evaluate the thermal performance of buildings' materials (Asan 2006; Mavromatidis et al. 2012).

Recently, it has been demonstrated that for complex envelopes, the time and amplitude of heat wave for different wall orientations in two different climates are dissimilar because of thermal storage (Mavromatidis et al. 2012). Also, by studying the energy consumption of three different walls in two different hot-dry and hot-humid climates, Yilmaz (2007) concluded that the walls with the same overall heat transfer coefficient have different heat losses because of the difference in thermal storage. Larsen and Lesino (2001) in their hourly analyzing program evaluated the effect of meteorological conditions on cooling and heating loads of buildings. Moreover, AL-Turkey and Zaki (1991) in their studies illustrated the effect of insulation and thermal storage in elements layers on cooling load of buildings.

In this study thermal performance of four roofs with different thermal capacities in different external conditions are compared. To this end, building energy simulation tool EnergyPlus is used to evaluate the time evolution of the heat gain of each roof in different conditions, i.e., low and high solar radiation and dry and humid climates. The intensity of absorbed solar radiation is influenced by clouds, shading from neighboring buildings, and light colored roofs. On the other hand, the climate mainly determines the outdoor temperature variation. The main question here is how changing the heat capacity of the roof affects the thermal performance of the roof in these conditions. In the following sections, the materials selected for the roofs and the external conditions are described and the results of the hourly analysis are discussed.

Problem Definition

Heat transfer through building envelopes such as roof and walls can be analyzed using either transient or steady approaches. Selection of the appropriate analysis method depends on external conditions and the goal being pursued. Here, a transient hourly analysis is carried out using the well-organized and powerful tool EnergyPlus which was developed in the US Department of Energy (DOE) in the 1990s. It works based on the combination of two energy modeling programs BLAST and DOE-2 which were developed by the US Department of Defense and the DOE respectively in the 1970s. The heat flux through the roof is computed by the Conduction Transfer Function (CTF) method.

A fully adiabatic small office room except roof with total surface area 17.2 m^2 has been modeled in the Google SketchUp. The geometry of the room is represented in Figure 1. The external surface of the roof is exposed to the convection heat transfer, solar radiation and reflected radiation from the surface. For simplicity, it is assumed that temperature variation is one-dimensional. In fact, the assumption of the one-dimensional problem is not the case for the actual condition including stud-and-block roofs. However, in these types of roofs, some portion of the area is occupied by studs which are usually made of the identical materials in different types of roofs. Further, the portion of this part is generally less than that of the blocks. Thus, in this study, only heat transfer through the blocks is investigated.

Also, the following assumptions are considered:

1. Solar radiation and ambient temperature vary periodically with time.
2. The material properties are constant.
3. The indoor temperature is kept constant by a proper cooling system.

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4. The radiation heat transfer at the inner surface is neglected.
5. Thermal conductivity and other material properties are not a functions of temperature as the temperature variation in each layer is small.

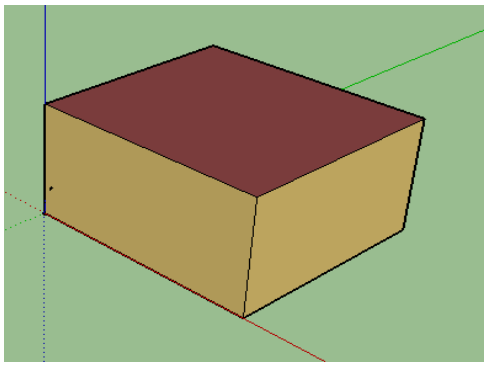

Figure 1: Small office room model

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Materials

The schematic of the multi-layered roof investigated in this paper is show in in Figure 2. In the Middle East, the use of manufactured blocks in roofs has significantly grown. This kind of roof has suitable acceptability because of good resistance against earthquakes.

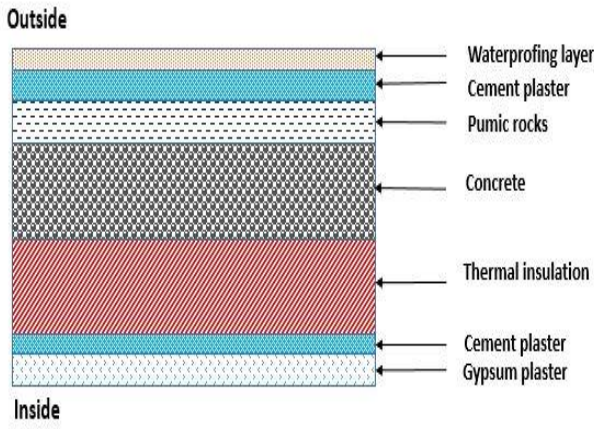

Figure 2: Schematic of the multi-layer roofs

In this study, four roofs with different thermal capacities are considered. The properties of the employed materials are listed in Table 1 according to the data given in Iranian National Building Codes (2010). As described in Table 1, all the roofs have the same composition. The difference between them is the thickness of concrete layer and expanded polystyrene block which are denoted by *x* and *y* respectively. These parameters are chosen in such a way that the overall heat transfer coefficient would be equal to 0.2 W/m^2 K while they have different heat capacities. The values are reported in Table 2. In the last column of this table we define a non-dimensional parameter C*=C/UT where T is period and equal to 24×3600 seconds. Hereafter, we use this parameter as a representative of the heat capacity.

Table 1: Details of layers' thermal properties used for two types of roofs.

Layer No.	Materials	Thickness (mm)	k ($\frac{W}{m.K}$)	C_p ($\frac{kJ}{kg.K}$)	ρ ($\frac{kg}{m^3}$)
1	Waterproofing layer	5	0.15	0.9	2500
2	Cement plaster	20	1.15	1	2100
3	Pumice rocks	75	0.15	0.9	600
4	Concrete	x	1.79	0.85	2300
5	Expanded polystyrene	y	0.04	1.21	40
6	Cement plaster	15	1.15	1	2100
7	Gypsum plaster	10	0.36	1	1300

Table 2: Thickness of concrete and expanded polystyrene layer and overall thermal properties of each roof.

Roof type	x (m)	y (m)	C (kJ/m^{2}K)	U (W/ m^2K)	ρ ($\frac{kg}{m^2}$)	C*
1	1	176	167	0.2	153	9.7
2	50	175	245	0.2	266	14.2
3	175	172	555	0.2	553	32.1
4	250	170	712	0.2	725	41.2

Climate conditions

In this paper, two climates are considered; hot-humid and hot-dry conditions that are indicated with abbreviations H and D, respectively. The representative city for the hot-dry climate has latitude and longitude 36.8° N and 115.15° W. The altitude and longitude for the hot-humid city are 13.92° N and 100.6 ° E respectively. Figure 3 shows the ambient temperatures versus time for the selected climates.

As illustrated in Figure 2, in the hot-humid climate, due to high latent heat the temperature difference between day and night is lower than that of the hot-dry climate. On the

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other hand, as described in the next subsection, the solar radiation in the hot-humid climate in this study is higher due to the lower latitude angle. So, in terms of total cooling load, these two climates are comparable.

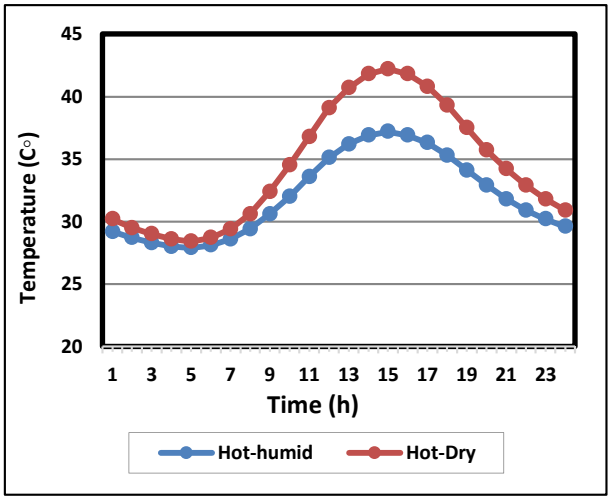

Figure 3: Ambient temperatures variations for the two selected climates for 21 July based on Ref. (EnergyPlus)

Solar radiation

Solar radiation incident to the surface consists of short wave radiation that can be absorbed and reflected and comes to the building and influences the internal and external surface temperature (Shen et al. 2011). A portion of the heat absorbed by the outer surface is transferred to other layers by conduction. The other part may release through convection and long wave radiation to the sky.

The total solar radiation consists of three parts; direct radiation G_D, diffuse radiation G_d, and ground-reflected radiation G_g.

$$G_T = G_D + G_d + G_g \quad (1)$$

Ground-reflected radiation G_g for a horizontal surface is 0. So, in this study, it is ignored.

Here, two high and low conditions for solar radiations are considered. High-radiation in this case is when both the direct and diffuse radiations are considered and the color of the roof surface is black with emissivity coefficient ε equal to 0.9. For the low-radiation condition only the diffuse radiation is considered, with a white color surface for which ε is 0.2. These two conditions in this paper are denoted by H and L, respectively. The comparison was carried out on 21 July as the solar radiation intensity on the horizontal surface is maximum on this day.

Value of the solar radiation varies with time and depends on climate and places. The components of solar radiation are shown in Figure 3 for the above selected cities based on the data from EnergyPlus. In Figure 4 it is seen that there is a delay for the time that solar radiation reaches its peak in both climates. The reason is that there is a difference between the local solar time (LST) and local civil time (LCT), which is indicated by the clock. The LST is based on the apparent daily motion of sun in the sky, and the difference between these times is because of irregularities of earth orbit and tilt of its axes. Here, one hour is the difference between two climates for the solar radiation peak.

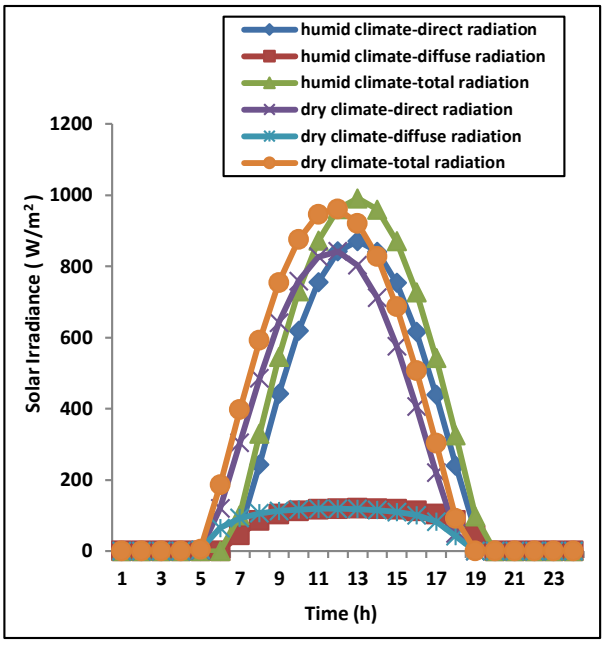

Figure 4: The solar radiation components for the two selected climates based on Ref. (EnergyPlus).

Performance Indices

To analyze the results, the variation of the temperature through the envelope is described by propagation of waves. In this way, the magnitude of the waves represents temperature. The amplitude of heat waves at the outer surface depends on solar radiation and convection heat transfer with outdoor air temperature. While the wave propagates through the roof toward the inner surface, the magnitude of the temperature waves and the amount of the net heat transfer rate decreased because of thermal storage. In other words, when the wave reaches the indoor space, its amplitude is less than that on the external surface (Asan 2006). The decrease in the ratio of temperature value during transient process is called "decrement factor" (Asan and Sancaktar 1998) i.e.,

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$$f = \frac{T_{i,max} - T_{i,min}}{T_{o,max} - T_{o,min}}, \quad (2)$$

where $T_{o,min}$, $T_{o,max}$, $T_{i,min}$, and $T_{i,max}$ are the maximum and minimum amount of temperature on exterior and interior roof boundaries, respectively.

In addition to the reduction of wave amplitude, the phase of the wave is delayed with the propagation of the wave. The difference between the times that maximum or minimum temperatures of outside conditions reach the inside is called "time lag" ϕ. Following Asan and Sancaktar (1998), here, these factors are defined as:

$$\phi_{max} = t_{i,max} - t_{o,max}\ , \qquad \phi_{min} = t_{i,min} - t_{o,min}, \quad (3)$$

where $t_{i,max}$, $t_{o,max}$, $t_{i,min}$ and $t_{o,min}$ represent the times that outside and inner side of roof surface reach their maximum and minimum respectively. The above defined factors depend on the thermal properties, thickness of roof layers and solar absorptivity, which are important in the selection of the cooling system. The time lags, decrement factor, and schematics of temperature oscillations are shown in Figure 5.

When the outside boundary condition is time-periodic and harmonic, ϕ_{max} and ϕ_{min} are the same. In this situation, the pseudo-steady state solution of the governing differential equation (4) is achievable. Although the variation of ambient temperature (Figure 3) may be approximated with a sine-type function, in the presence of the solar radiation, the outside condition is not a harmonic function (Larsen et al. 2009; Mavromatidis et al. 2012). Hence, ϕ_{max} may be unequal to ϕ_{min} .

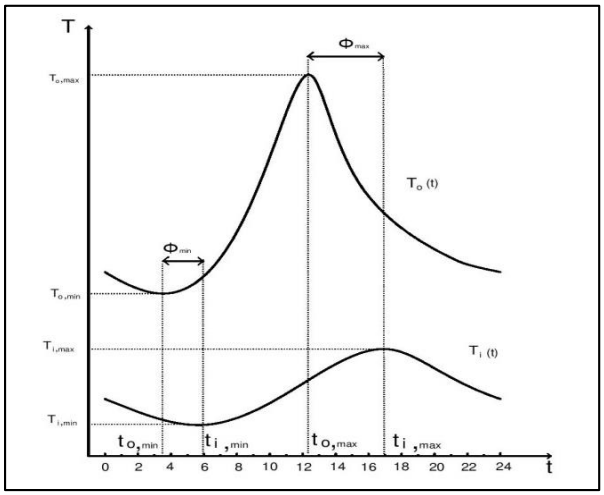

Figure 5: The schematic representation of the temperature oscillation on inner and outer surface of the roof and definition of the time lags $\boldsymbol{\phi_{max}}$ *and* $\boldsymbol{\phi_{min}}$.

Results and Discussion

The introduced roofs the analyzed hourly by EnergyPlus in different conditions. The obtained results are plotted in Figure 6 to Figure 11. In this section, the results are examined in three categories.

Heat gains

In Figures 6 and 7, the maximum and minimum heat transfer rates at the inner surface during the day of the test are reported for all the roofs for both climates and high- and low-radiation conditions respectively. The results in these figures demonstrate that by increasing the heat capacity, the difference between maximum and minimum heat rates reduces steadily in both climates while it is more evident in the hot-dry climate. Similar results can be seen in Figure 7 for the low-radiation cases. However, in this condition, the differences Δq are much less than the corresponding values for the high-radiation condition The difference between the maximum and minimum heat rates in the dry climate is more than the humid climate due to the higher temperature difference during the 24-hours in the dry area (See Figure 3).

Also in Figures 6 and 7, average heat transfer rates are plotted versus C*. This average is calculated by dividing the total load of each case to the time period (i.e., 24 hours). Hence it represents the overall heat gain through the roof. It is seen that in the high-radiation condition (Figure 6) the total load slightly decreases by increasing the heat capacity of roofs while the overall heat transfer coefficient is constant. Nevertheless, in the low-radiation condition, in both climates, averages of heat flux are not meaningful functions of the thermal storage of the roof.

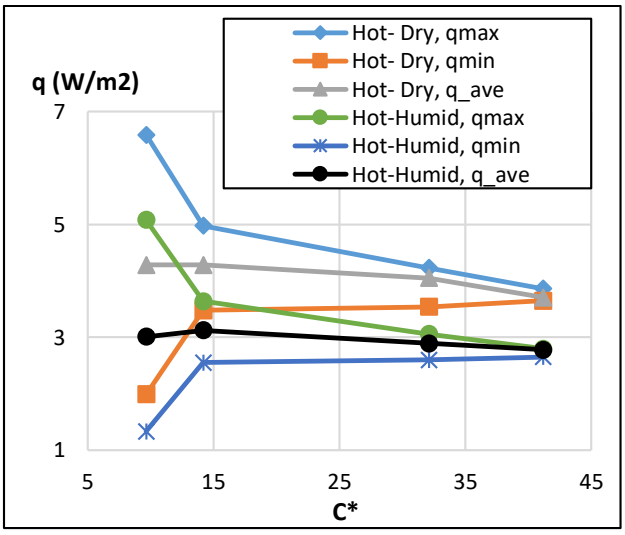

Figure 6: Maximum, minimum and average heat flux variation with thermal capacity for high-radiation condition in both climates.

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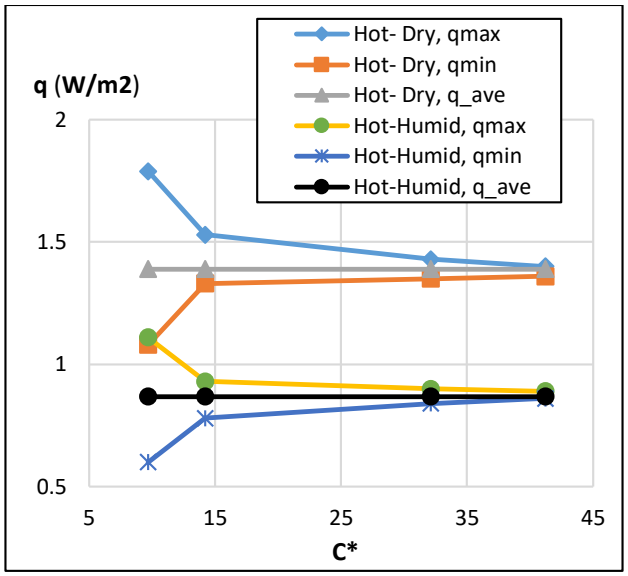

Figure 7: Maximum, minimum and average heat flux variation with thermal capacity for low-radiation condition in both climates

Time lags and decrement factor

The time-variation of temperatures can be explained by the time lags ϕ_{max} and ϕ_{min}. If one simulates the behavior of the roofs by a series of resistances paralleled with capacitors, it can be shown that the phase lag between temperature difference and heat rate is a function of resistance multiplied by capacity similar to the Resistance-Capacitor (RC) electrical circuits studied in the context of alternating currents (AC) circuits (Hayt et al. 2012). In this way, time lags for the roof type 4 are expected to be more than other types. Because all roofs have the same total resistance but the thermal capacity of roof 4 is much more. The results in Figure 8 confirm the above statement.

On the other hand, the results in Figure 9 show that in the low-radiation condition, ϕ_{max} and ϕ_{min} are the same. The reason is that without the presence of direct solar radiation, the external condition can be estimated as sine-type. Consequently, the problem is completely similar to the aforementioned AC circuit and the time lags are equal. However, direct solar radiation affects this similarity.

Since the radiation profiles in Figure 4 are obviously not sine-type, ϕ_{max} and ϕ_{min} are not equal for the cases with high-radiation. The results in Figure 8 shows three or two hours difference between ϕ_{max} and ϕ_{min} for the high-radiation condition. The fact that ϕ_{max} is greater than ϕ_{min} has also been stated in the literature. For instance, see Mavromatidi et al. (2012). However, ϕ_{min} is one hour more in the dry climate cases than their humid counterparts.

Apart from these parameters, decrement factor is another important parameter in the evaluation of material performance in buildings and the lower amount for this factor is desirable. As shown by Asan (2006), by decreasing the thermal capacity, the decrement factor increases. It is in agreement with the results in Figure 10 and Figure 11 in which the decrement factors are plotted versus thermal capacity in semi-log charts.

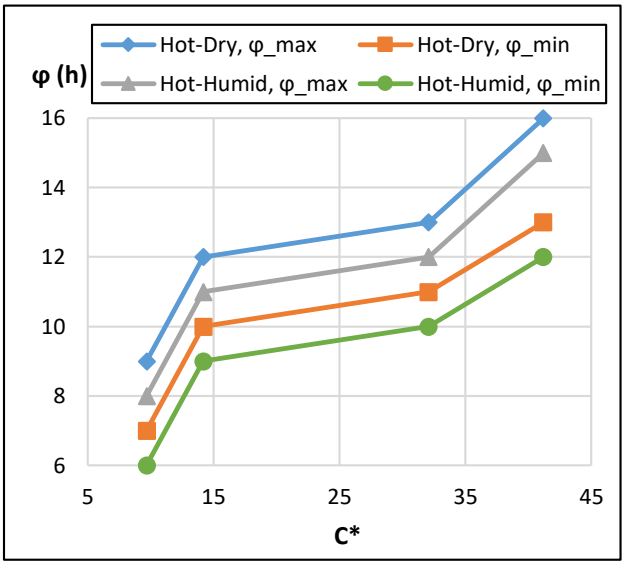

Figure 8: Time lags variation with thermal capacity for high-radiation condition in both climates.

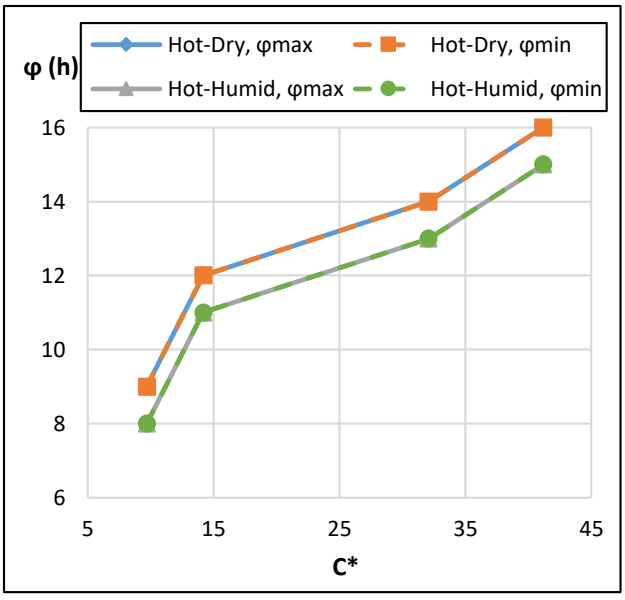

Figure 9: Time lags variation with thermal capacity for low-radiation condition in both climates.

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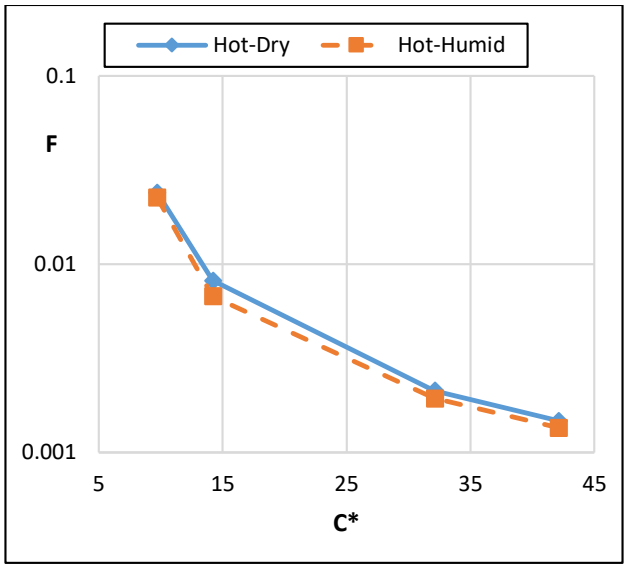

Figure 10: Decrement factor vs. thermal capacity for high-radiation condition in both climates.

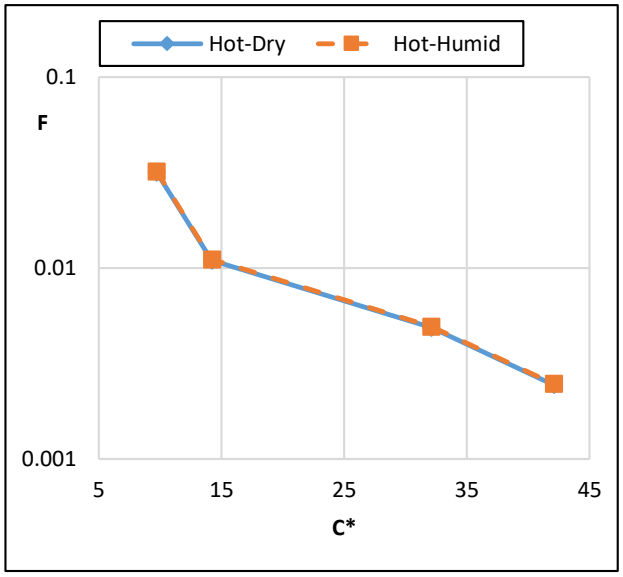

Figure 11: Decrement factor vs. thermal capacity for low-radiation condition in both climates

Energy benefits

The results showed that in the high-radiation condition the roofs have considerably higher load compared to the low-radiation condition. It can be concluded that using the solar shading as well as light colored surfaces are appropriate strategies for reducing the cooling load in these kind of climates. For instance, the total load was reduced by 64% in all cases in both climates when the passive strategies have been applied to the roof.

We observed that the inner surface temperature starts to decrease from the latest hours of the night to the afternoon. For example, in roof type 4, in the dry climate and high-radiation condition, the maximum inner surface temperature occurred at 4 a.m. and the minimum inner temperature occurred 4 hours after the outer surface reaches its maximum value. After 4 p.m. the inner surface increases gradually to the middle of night at 4 a.m. which causes the high ϕ_{max} because the outer surface reaches its maximum value early. This behavior of the roof shows that during the time that the inner surface temperature is decreasing, it absorbs the energy and then releases it in the middle of night.

It can be inferred that although the thermal capacity was not useful in reduction of load, the higher heat capacity results in more time lags as well as reduction of energy consumption and electricity cost in both climates. To illustrate, the maximum load occurs during the middle of night while the cooling energy consumption is minimal, and the minimum load occurs during the warm hours of day where the energy consumption is high. Therefore, as the roof has a great deal of heat gain for the hot dry and humid climates, it is recommended using the roofs with higher thermal capacity as well as providing solar shading and using light colored surfaces for the roofs to reduce the energy consumption in buildings in these regions.

Conclusions

In this paper, the effect of heat capacity of the roof on its thermal performance under different conditions is investigated using EnergyPlus. The studied conditions are high and low radiation intensities in hot-dry and hot-humid climates. Here, the low-radiation case is achievable by solar shading and using light colored surfaces. The thermal properties examined are minimum, maximum, and average heat fluxes, time lags, and decrement factors. The results are summarized below.

- As it is expected, the main effect of the heat capacity of roof is to decrease the difference between its maximum and minimum loads especially in the dry climate and high-radiation condition. However, the reduction in the total load is observed only in the high-radiation case and its magnitude is not significant.
- The heat flux reduces considerably when the the passive strategies are considered.
- Environmental conditions such as ambient temperature and solar radiation change the time lags. In the high-radiation condition ϕ_{max} and ϕ_{min} are not equal to each other, being $\phi_{max} \geq \phi_{min}$.This happens because the external condition is not

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sinusoidal. However, in the low-radiation, the ϕ_{max} and ϕ_{min} are equal to each other in both climates.

- Decrement factors reduce exponentially by increasing the heat capacity. However, the external conditions have a slight effect onthe decrement factors.
- Since cooling system size is determined for the peak load in summer, high ϕ_{min} is better because the minimum indoor temperature occurs in hottest external condition, and vice versa. From this point of view, the roof with higher heat capacity has better performance.

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