Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Simulating the effects of cool roof and PCM (phase change materials) based roof to mitigate UHI (urban heat island) in prominent US cities

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ARTICLE INFO

Article history:

Received 8 July 2015

Received in revised form

22 October 2015

Accepted 28 November 2015

Available online xxx

Keywords:

Cool roofs

PCM roofs

Envelope materials

Urban heat island

Sensible heat

Roof surface temperature

ABSTRACT

UHI (Urban Heat Island) has become a serious concern within major cities due to the increased threat of climate change over time. As UHI intensifies, the energy consumed in urban areas increases through an increase in the cooling demand, and restricts the overall comfort and quality of life in urban regions. UHI mitigation approaches have been widely studied over the past few decades. However, the work presented here evaluates and compares how PCM (cool roof and phase change materials) based roof technologies may perform as UHI mitigation strategies. Detailed thermal energy simulations were conducted with these two strategies over a range of seven climatic zones within the United States. For each mitigation strategy, five different roof types were chosen for the analysis. The results indicate that a higher albedo led to superior energy saving and UHI mitigation for all types of roofing materials. Also, asphalt roofs produced the best results of all the roof types. It was found that insulation did not play a significant role in the reduction of UHI effects. The maximum TRHG (through roof heat gain) flux was 54% lower for the PCM roof than the cool roof at a wide range of albedo. Similarly, the maximum sensible heat flux for the PCM roof type 40% lower than the cool roof technology for varying albedo.

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1. Introduction

The heat island effect describes how densely packed urban areas are warmer than in surrounding rural regions. Densely positioned buildings and structures within urban areas absorbing solar radiation in the form of heat, a lack of vegetation or green space, and the heat generated from environmental pollution are all direct contributors towards this urban heat phenomena. This issue affects the majority of the population within the United States of America. The United Nations Population Division reported that in United States of America urban population was approximately 81.4% for the year of 2014 and estimated that the urban population will continue to increase to 87.4% by the year 2050 [1].

For decades, researchers have studied UHI (Urban Heat Island) effects [2–8], and still the main mitigation concept was conceived during ancient Greek times [9]. The use of materials with a high solar reflectance (albedo) for roofs within urban regions can significantly affect the micro-climate of an urban area, mostly due to the large surface area of roofs within urban areas [10]. Akabari

et al. [11] estimated a roof surface area as high as 25% in densely populated cities within the United States. Thus, the technological advancement of cool materials, or materials with high solar reflectance and infrared emittance, has been a continued effort around the world. Cool material technology presents a cost-effective, environmentally friendly, passive technique that can significantly impact the energy consumption of individual buildings, as well as the overall climate of urban areas [12,13]. The primary objective of cool or reflective roof technology is to increase the albedo. Typically, this is done by applying a liquid material (white paint, elastomeric, polyurethane, acrylic coatings), or by using single ply product (Ethylene-Propylenediene-Tetrollymer Membrane, Polyvinyl Chloride, Chlorinated Polyethylene, Chlorosulfonated Polyethylene, Thermoplastic Polyolefin) [9]. However, this technique has evolved over the years as more and more highly reflective materials are discovered. Most recently, advances in nanotechnology has lead to the conception of highly reflective thermochromatic paint [14]. Thermochromatic paints are designed to be thermally reversible, meaning that during the hot summer months the cool roof will have a high reflectivity and during the cold winters, a high absorption rate. Although currently more expensive, this technology does present a significant advantage

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Nomenclature			
C	specific heat	T_a	outside air dew-point temperature
Gr_{L_n}	Grashof number, $g\rho^2 L_n^3 \Delta T / T_f \mu^2$	T_f	roof surface film temperature—average of roof temperature and outside air temperature
g	gravitational constant	T_r	roof outside surface temperature
h_r	heat transfer coefficient	x	distance along wind direction from roof edge to convection coefficient evaluation point
k	conductivity of air	x_c	critical length
L_n	characteristic length for natural convection, (area-to-perimeter ratio)	u	free-stream wind speed at roof level
Nu	Nusselt number	ΔT	roof outside surface temperature minus outside air temperature
Pr	Prandtl number	β	weighting factor for natural convection
$q_{r,s}$	sensible heat flux	μ	viscosity of air evaluated at T_f
$q_{r,g}$	through roof heat gains flux	ρ	density of air evaluated at T_f
Ra	Rayleigh number	ε	emissivity
Re_x	Reynolds number	HVAC	heating, ventilation, and air conditioning
R_f	surface roughness factor	TRHG	through roof heat gains

over its competitors [14]. However, another mitigation technique (i.e. PCM (phase change materials) roof), while not nearly as longstanding as the “cool roof” technology, provides an alternative solution. PCM possesses high latent heat capacity that makes it feasible to use as an energy storage media in building envelope.

The use of PCM for thermal energy storage was introduced around the 1980s [15]. More recently, the use of PCM has been experimented within the envelope of the roof in an attempt to reduce energy consumption [16], [17]. PCM can be enclosed within the roofs of buildings which might play a large role towards thermal balance. These materials absorb solar and infrared radiation and release a portion of the accrued thermal energy through convective and radiative processes into the atmosphere. PCM can be sub-divided into three main categories based on the chemical structure (organic, inorganic, and eutectic mixtures) [18]. Fundamentally, PCM technology partially absorbs cool energy from air conditioning systems or free cooling (storage of cool energy overnight) and helps to maintain that temperature throughout the peak hours of the day, thereby increasing thermal comfort [19]. The chemicals within the PCM undergo a cycle of phase changes to continually reduce the effect of outdoor temperatures on indoor temperatures, delay the peak heat loads, as well as stabilizing the interior temperature [20]. PCM does this not by affecting the thermal resistance of a roof, but rather by influencing the surface temperature [18]. While increasing the albedo of a roof will reduce the cooling load of buildings, there may be a potential need for an increase in heating needs over the course of winter.

The effects of roof technology on UHI result from an interplay of several causes. Absorption of short-wave solar radiation, anthropogenic heat released from the built environment, a decrease in latent heat due to lack of moisture sorption in urban materials, and change in urban forms are all contributing factors to UHI [21–23]. The roof technologies studied in the present work can affect one or multiple of these causes. Both cool roof and PCM roof can help to decrease the cooling load demand. The cool roof approach can reduce the amount of absorbed radiation, and the PCM approach can reduce the sensible heat by introducing latent heat gains of the PCM. Three metrics were chosen to help monitor the effectiveness of the various roof types that incorporate these technologies: TRHG (through roof heat gain) flux, roof surface temperature, and sensible heat flux.

In the work reported here, thermal energy modeling was utilized over a wide range of climatic zones across the United States of America to determine the effectiveness of cool roof vs. PCM roof technologies in mitigating UHI effects. Roof surface temperature,

thermal energy entering the room via the roof, and sensible heat flux were analyzed at these different climatic regions. These thermal measurements were again examined with various PCM materials within the envelope of the roof. Metal, concrete, built-up (combination of tar and gravel), asphalt shingles, and Single Ply Membrane roof types were the cool roof types that were evaluated within the analysis, while BioPCM, Enerciel22, CaCl₂·6H₂O, Eutectic salt and Paraffin were the various types of PCM roof materials evaluated. Lastly, a parametric analysis was performed on the effects of albedo on PCM variations and roofing materials. The goal of this research was to enlighten a large and thermally diverse nation of improved approaches towards reducing commercial and industrial energy costs.

2. Methodology

2.1. Simulation

In this study, dynamic thermal behavior for various roof types was simulated within DesignBuilder, a graphical interface coupled with the popular EnergyPlus energy simulation software. EnergyPlus is frequently used to model and simulate building energy consumption. It has the capability to accurately model the energy flow between a building and its environment. Unfortunately, the required level of expertise for EnergyPlus is a significant hurdle for nontechnical users mainly due to the many intricate decisions that are required to produce an accurate model. Fortunately DesignBuilder provides a wide breadth of features that enables a more user-intimate environment. DesignBuilder was designed around EnergyPlus, and thus still uses EnergyPlus as its heat simulation engine. This powerful software was largely used to calculate and graphically illustrate the sensible heat flux, surface temperature and heat gain incident on the roof for various cool/reflective materials.

2.2. Building model

The DOE (Department of Energy) has graciously provided fifteen ‘benchmark building’ files for public usage within the EnergyPlus simulation environment [24]. These models, although extremely convenient for simple simulations, lack the necessary detail to reflect the intricacies of a commercial/industrial building. To improve the resolution and detail of the system, a typical hospital building floor plan was used as a reference to model a more commonly seen edifice. This is much more detailed than a standard

Fig. 1. This illustration provides a detailed graphical explanation of the various types of materials that were incorporated throughout this thermal simulation study.

Table 1
Reference building characteristics used for EnergyPlus simulations.

Types	Characteristics	Descriptions
Forms	Building type Surface area Orientation	Hospital 1080 m ² E–W
Envelope	Walls Roof Floor	Stucco, Insulation, gypsum board, total U = 2.53 W/m ² -K, surface area 2063 m ² Roof membrane, insulation, metal decking, total U = 3.45 W/m ² -K, surface area 560 m ² Concrete floor with carpet, U = 1.94 W/m ² -K
HVAC	Windows Heating type Cooling type Distribution and terminal units	ECREF-2 colored glass windows, total U = 3.43 W/m ² -K, surface area 119 m ² Gas furnace inside the packaged air conditioning unit Packaged air conditioning unit VAV terminal box with damper and electric reheating coil

box-like structure. Also, a hospital floor plan makes sense to use as it is the type of facility in which a great deal of time and care would have gone into managing the amount of energy consumed throughout the year. Further detail was implemented via the manual creation of various types of roofs within DesignBuilder. Fig. 1 illustrates some of the roof designs that were utilized within this study. Several different rooftop materials were considered along with several different PCM materials. The steep slope rooftop was chosen to be asphalt shingles which represents the most common material for steep slopes.

Detailed specification of the two-level hospital building including building surface area, orientation, building envelope features and HVAC system setting are tabulated in Table 1. Thermostat settings and operation schedules were taken from DOE benchmark building information. As mentioned before the simulation was conducted by using DesignBuilder. However to better visualize the floor plans and 3D model, which is shown in Figs. 2–4, a commercial software Revit was used to depict the same model as it was used in DesignBuilder. During the simulation all the building features were kept constant except only designated roof type was changed. It should be noted that the modeling and building characteristics outlined in this paper can be used to any residential or commercial building prototype.

2.3. Climate data

Energy consumption within urban areas is expected to increase during the summer months. The days that yield the highest

ambient temperature and the strongest solar radiation naturally equate to the days that yield the greatest amount of energy consumed. Typically, the seven hottest days of summer range from July 23rd through July 30th. An analysis of the energy consumed on these particularly hot days could lead to the curtailing of energy consumption related expenses in buildings within urban regions. However, when comparing the thermal effects of urban regions across a country as large and climatically diverse as the United States, it's important to take into account the climate difference

Fig. 2. A 3D rendering of the building considered in this study, created in Revit. It is a two level hospital-type floor plan.

Fig. 3. The ground-floor plan of the building considered in this study, showing dimensions and intended uses, for simulation in DesignBuilder software.

between the regions of interest. Thus, in an effort to account for this, cities from varying climate zones were taken into consideration. Fig. 5 illustrates a climate zone mapping of the United States [25], while Table 2 shows seven major cities within each climatic region. Designbuilder simulation results were collected in 30-min intervals over the seven warm days of the summer (July 23rd to July 30th). From this table, each city was used for thermal simulations. For each major city that was considered, the sensible heat flux, TRHG flux, and roof surface temperature for a variation of albedo, roof types, insulation, and PCM were recorded.

2.4. Heat transfer theory

Although EnergyPlus is vastly popular, and powerful, it's method for solving the heat transfer coefficient at a particular point

on a roof only takes into consideration when the air above the roof is turbulent due to natural convection. Clear et al. [26] went a step further and mathematically explained the case for when the air above the roof does not produce turbulence. Although this may be a less common occurrence, it could happen and thus should be accounted for [26,27]. Sensible heat flux refers to the convective heat flux from the roof surface to the ambient air can be described by equation (1).

$$q_{r,s} = h_r(T_r - T_a) \quad (1)$$

where, T_a is the ambient air temperature which can be found from the TMY3 weather file for different US cities [28] and T_r is the roof surface temperature which was found from the simulation results of Designbuilder software.

Fig. 4. The first-floor plan of the building considered in this study, showing dimensions and intended uses, for simulation in DesignBuilder software.

Fig. 5. This map of the United States indicates the seven different climatic regions [25].

Equations used to solve for the heat transfer coefficient, h_r , were based on standard convection heat flow relationships. These empirical relationships, found in Table 3, describe flow over a smooth, isothermal flat plate with its upper surface being cooled or heated, were used to decide the flow condition and Eq. (2) was used to calculate heat transfer coefficient.

The combination of the natural and forced Nusselt numbers led to equation (2) for the heat transfer coefficient [26],

$$h_r = \begin{cases} \beta \frac{k}{L_n} 0.15 Ra_{L_n}^{1/3} + \frac{k}{x} R_f 0.037 Re_x^{4/5} Pr^{1/3} & \text{When, } T_r - T_a \geq 0 \\ \beta \frac{k}{L_n} 0.27 Ra_{L_n}^{1/4} + \frac{k}{x} R_f 0.66 Re_x^{1/2} Pr^{1/3} & \text{When, } T_r - T_a < 0 \text{ and } x < x_c \\ \beta \frac{k}{L_n} 0.27 Ra_{L_n}^{1/4} + \frac{k}{x} R_f (0.0037 Re_x^{4/5} - 871) Pr^{1/3} & \text{When, } T_r - T_a < 0 \text{ and } x > x_c \end{cases} \quad (2)$$

where, β is a function which describes the relationship between the Grashof and Reynolds numbers, as shown in equation (3).

$$\beta = \frac{\ln(1 + Gr_{L_n}/Re_x^2)}{1 + \ln(1 + Gr_{L_n}/Re_x^2)} \quad (3)$$

The Reynolds number, Rayleigh number and Grashof number are described in equations (4)–(6) respectively.

$$Re_x = \frac{u \rho x}{\mu} \quad (4)$$

Table 2
Climate zones and their respective major cities.

Climate zone	Climate type	Corresponding major city
1	Hot-humid	Miami, FL
2	Hot-humid	Houston, TX
3	Hot-dry	Los Angeles, CA
4	Marine	Seattle, WA
5	Cold	Chicago, IL
6	Cold	Minneapolis, MN
7	Very cold	Fargo, ND

$$Ra = Gr_{L_n} Pr \quad (5)$$

$$Gr_{L_n} = \frac{g \rho^2 L_n^3 \Delta T}{T_f \mu^2} \quad (6)$$

3. Results and discussion

3.1. Cool roof

3.1.1. Effect of albedo variation

Thermal energy modeling was applied to determine heat generation within a typical hospital building. Standard cool roof Sensible Reflectivity (SR), Emissivity (ϵ), and SRI (solar radiation index) values were gathered from the Cool Roof Rating Council to be utilized within the simulations. Table 4 shows these optical properties for the cool roof based on built-up roof type.

Sensible heat flux, $q_{r,s}$ (i.e. heat flux from roof surface to the surrounding environment), TRHG flux, $q_{r,g}$ (i.e. heat flux to building

Table 3
Flat plate convective heat flow correlations [26].

Convection type	Range	Nusselt number (Nu)
Natural	$\Delta T > 0$, $10^7 < Ra < 10^{10}$ (turbulent)	$0.15 Ra^{1/3}$
	$\Delta T < 0$, $10^5 < Ra < 10^{10}$	$0.27 Ra^{1/4}$
Forced	$Re < 10^5$ (laminar)	$0.332 Re_x^{1/2} Pr^{1/3}$
	$10^5 < Re < 10^8$ (turbulent)	$0.0296 Re_x^{4/5} Pr^{1/3}$

Table 4
Optical properties of built-up roofs used for simulation.

Roof type	SR	ϵ	SRI	Color	Vendor/Source
Built-up Roof	0.3	0.9	31.8 ^a	Bright White	[29]
	0.5	0.86	57		[30]
	0.7	0.91	86		[31]
	0.86	0.82	107		[32]

Cool roof properties are taken from CRRC [30] and DOE medium office benchmark model [33].

^a SRI value was calculated by using ORNL SRI Calculator (ASTM E1980-01).

interior through the roof), and roof surface temperature, T_r were analyzed for the hospital building with various albedo values over a 24 h time interval during the hottest week of the summer. Sensible heat flux values were calculated by using Eqs. 1–6 and it accounts both the effect of forced and natural convection depending on the climatic condition. TRHG flux and roof surface temperatures were extracted directly from the simulation results. Additionally, TRHG flux was repeated for seven climatically diverse cities across the United States and then averaged at the peak hours to compare the results across each representative city. Fig. 6 provides a graphical sampling of the collected data. Fig. 6A shows the TRHG flux for Miami, Florida at varying levels of albedo. For this particular example, the greatest value of TRHG flux was 54.50 W/m², exhibited by the solar reflectivity of 0.3. As solar reflectivity of the roof type increased, the TRHG flux steadily decreased. Fig. 6B and C illustrate the roof surface temperature and sensible heat flux for varying levels of solar reflectivity respectively. Similar to the TRHG

flux plot, there is an analogous relationship in both surface temperature and sensible heat flux with solar reflectivity. Lastly, Fig. 6D shows the TRHG flux recorded for the seven cities (Miami, Chicago, Houston, Los Angeles, Minneapolis, Seattle, and Fargo). The average peak TRHG flux was higher for roofs with a lower solar reflectivity, regardless of the region. However, the average peak TRHG flux was the greatest in the southeastern region of the United States and lowest in the northwestern region. This could be attributed to geographical distance from the equator or cool winds blowing from the Pacific Ocean. Moreover in Fig. 6D it can be seen that in Los Angeles (e.g. a hot and dry climatic region) the difference of TRHG flux in between two extreme albedo (SR 0.3 and 0.86) roofing materials is 31.2 W/m², highest among all cities. Whereas in Miami and Houston (e.g. a hot and humid climatic region) the difference of TRHG flux are 19.1 W/m² and 15.7 W/m² respectively. From these results it can be inferred that humidity might have detrimental effects on both the energy saving and UHI mitigation especially for higher albedo roofing materials in hot climatic regions. It is also noticeable that for cold climatic regions like, Chicago, Minneapolis, and Fargo, the difference of TRHG flux between the two most extreme albedo values (SR 0.3 and 0.86) were 28 W/m², 23.5 W/m², and 24.1 W/m² respectively, which processes very similar behavior in energy saving and UHI mitigation.

A high albedo on the roof surface could potentially improve the lifetime of the roof. Lowering the albedo of roofing materials will impose higher roof surface temperature by solar radiation and could damage the roof by enhancing chemical reactions inside the roofing materials. Also, the roof might experience higher thermal

Fig. 6. This image shows a sample of the simulation results for Miami (A) sensible heat flux, (B) TRHG flux, (C) roof surface temperature, (D) and TRHG flux during average peak hours for seven major US cities for various solar reflectivity (albedo) values.

stress due to uneven thermal expansion. Fig. 6B shows the daily fluctuation of roof surface temperature. For higher albedo roofing material (SR 0.86) the temperature change is 12 °C, whereas for traditional lower albedo (SR 0.3) absorptive material the temperature difference is 38 °C. Therefore, roofing materials with a higher albedo will experience much less thermal fatigue.

Cool roofs are becoming very popular with the building service professionals as it maintains lower thermal stresses, lower energy cost, and higher UHI mitigation compared to any traditional radiation absorptive roof (e.g. typical gray concrete roof has SR 0.2, and asphalt roof has SR 0.05) [2,5,11]. Implementing cool roof in a new construction or during renovation could avoid any additional cost as it provides a competitive retail price. Additionally, implementing cool roof is environmentally friendly due to its prolonged lifecycle expectation.

Fig. 7 shows the simulation results of roof surface temperature and TRHG flux over a 24 h period for the seven major cities listed in Table 2. These plots helped to expose further subtle differences between climatic regions. During simulation, solar reflectivity values were kept constant at 0.7 for those cities to capture the effect of the different climatic zone on UHI mitigating parameter (roof surface temperature) and energy saving parameter (TRHG flux). TRHG flux was chosen over sensible heat flux since sensible heat flux is a function of roof surface temperature and related by a factor of heat transfer coefficient only. The relationship between those two properties is explained further in details in section 3.1.2. TRHG flux was also evaluated in cool roof analysis for all climatic zones as shown in Figs. 6, 8 and 9.

3.1.2. Effects of roofing materials

Sensible heat flux, TRHG flux and roof surface temperature, were modeled for a set of differing roof materials/type. EnergyPlus simulations were performed over the same 24 h time interval during the hottest week of the summer that was used previously in section 3.1.1, and repeated for the seven climatically diverse cities stated in Table 2. Fig. 8 provides a graphical sampling of this data set. This particular example was based on the climate of Houston, TX.

Table 5 shows the optical and thermal properties of different roofing materials that were used in this study. Properties were taken from the vendor database of cool roof rating council [30]. Since solar reflectivity is the key measure of cool roof classification, its value for any particular roof type was chosen approximately around 0.625 ± 1.5 . It is also noticeable that solar reflective index, SRI (i.e., it incorporates solar reflectivity and emissivity) has almost

the same magnitude of 74.5 ± 3.5 for different roof types. SRI values also confirm that the contribution of solar radiation is equivalent for all roofing materials. In Table 5, other relevant properties of roofing materials are listed, e.g., thermal conductivity and volumetric heat capacity (i.e., a product of specific heat and density). Thermal conductivity can be used to measure the amount of heat flow through the roofing material. And volumetric heat capacity (i.e., a product of specific heat and density) is used to calculate the amount of heat stored in the roofing materials while undergoing a given temperature change. The ratio of thermal conductivity and volumetric heat capacity is defined as thermal diffusivity and it specifies how rapidly a spatial temperature difference equalizes in a roof layer.

The simulation results shown in Fig. 8A indicate that metal roofs give the highest TRHG flux, followed by the concrete tile, and the lowest is in asphalt shingles roofs over the 24-h interval. These simulation results can be interpreted by thermal conductivity and thermal diffusivity values of different roofing materials; metal roofs shows the highest peak hours TRHG flux due to its higher thermal conductivity and diffusivity. Since both thermal conductivity and diffusivity are responsible for the heat flow through the roof from outside to building interior, higher values of those properties have detrimental effects on building energy saving. Similarly, results of other roofing materials can also be explained by thermal conductivity and diffusivity values as listed in Table 5.

Fig. 8B and C showed the surface temperature and sensible heat flux respectively. In this instance, the results for all roofing materials matched closely. However, the metal roof showed slightly higher values in both categories compared to other roof types, while the asphalt shingle roof showed the lowest surface temperature and sensible heat flux. Similar results of sensible heat flux and roof surface temperature for different roofing materials can be explained by equivalent solar radiative properties as shown in Table 5. In Fig. 8B and C, both sensible heat flux, and roof surface temperature values show a similar behavior since both parameters only differ by a factor of heat transfer coefficient as shown in Eq. (1), provided that ambient temperatures are same in both instances. Since TMY3 weather data [28] for Houston was taken as an input for simulation, ambient temperature is same in both instances. Therefore, sensible heat flux and roof surface temperature are related by only a heat transfer coefficient parameter.

Fig. 8D describes a comparison between the various roof types across each city. Each city was in agreement that metal roof gained the most heat, followed by concrete tiles, build-up roof, the single ply membrane, and lastly the asphalt shingle. Regionally, the

Fig. 7. Simulation results of cool roof with SR = 0.7 for different US cities for (A) roof surface temperature, (B) TRHG flux.

Fig. 8. This image shows a sample of the simulation results for Houston (A) sensible heat flux, (B) TRHG flux, (C) roof surface temperature, (D) and TRHG flux during average peak hours for seven major US cities for various roof materials.

highest amount of heat gained by the tested roofs was in Miami, followed by Houston, Chicago, Los Angeles, Minneapolis, Seattle, and Fargo.

3.1.3. Effects of insulation

The addition of insulation can significantly affect the amount of heat transfer through a roof. Fig. 9 illustrates this effect on TRHG flux, roof surface temperature and sensible heat flux for varying degrees of insulation. Fig. 9A shows that as the R-value of the insulation increases, the TRHG flux decreases. R-value is a measure of resistance to heat flow through a given thickness of the material. It is the ratio of material thickness and thermal conductivity. For the same thickness materials, R-values dictate how well these materials can resist the heat flow. However, the same is not true for surface temperature and sensible heat flux. In Fig. 9B and C, there are little difference between varying degrees of insulation. These simulation results suggest that while the addition of insulation is great for reducing the TRHG flux, potentially increasing energy savings and overall roof efficiency, it has little effect on reducing the UHI effect. Especially during peak hours in the day, lower insulation levels increase the heat flow from the exterior roof surface to the building interior, which increases the energy cost considerably. Furthermore, as higher insulation resists the heat flow through the roof, it causes slightly higher roof surface temperature than a roof with lower insulation. Also, with the increase of roof surface temperature surrounding environment will experience a small rise in sensible heat flux. Implementing higher insulation, however, reduces the energy cost significantly as it can be inferred from the

peak hours TRHG flux as shown in Fig. 9A. Fig. 9D shows TRHG flux for insulation variation among different US cities. For each city, TRHG flux decreases with the increase of R-value and it shows a similar pattern for all the cities.

3.2. PCM

For any particular type of PCM, the storage system has to be sized appropriately before it is possible to implement it to a roof structure. The thickness of two commercial PCM, BioPCM@M182Q21 and Enceiel 22, were taken from the manufacturers database. Optimum thicknesses of the remaining PCM roof types were calculated using the relationship proposed by Peippo et al. [38]. Equation (7) was used to calculate the thickness of inorganic ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$), organic (Paraffin) and eutectic (Eutectic Salt) PCM roof types based on the assumption that the PCM slab needs to melt and solidify during any single day.

$$t_{\text{opt}} = \frac{t_n h_r}{\rho L} (T_{\text{PCM,opt}} - T_n) \quad (7)$$

where, $T_{\text{PCM,opt}}$ is the optimum phase change temperature of PCM roofing, T_n is nighttime temperature, t_n is PCM discharging time during night, ρ is PCM density, L is the PCM latent heat capacity, and h_r is heat transfer coefficient.

Table 6 shows the optical and thermophysical properties of various PCM materials that were used for the simulation. The most important parameter impacting the effectiveness of PCM roofing is

Fig. 9. This image shows a sample of the simulation results for Chicago (A) TRHG flux, (B) roof surface temperature, (C) sensible heat flux, (D) and TRHG flux during average peak hours for seven major US cities for various thicknesses of insulation.

Table 5

Optical & thermal properties for different roof types used for simulation.

Roof type	SR	ϵ^b	SRI	k W/m/K	C J/Kg/K	ρ Kg/m ³	R_f [34]	Color	Vendor/Source
Asphalt Shingles (AS)	0.62	0.9 ^b	74.7 ^a	0.04	1260	1120	2.17	White	[35]
Built-up Roof (BR)	0.62	0.87	74	0.16	1460	1120	1.67	Bright White	[31]
Single Ply Membrane (SPM)	0.64	0.91	78	0.17	900	1390	1.13	Tan	[36]
Concrete Tile (CT)	0.62	0.88	74	1.5	1000	2100	1.52	Off-White	[30]
Metal Roof (MR)	0.61	0.83	71	17	460	7900	1.11	Off-White	[37]

Cool roof properties are taken from CRRRC [30].

^a SRI value was calculated by using ORNL SRI Calculator (ASTM E1980-01).

^b Emissivity value was taken from DOE building benchmark model [33].

the PCM latent heat capacity, L , as the PCM uses the latent heat capacity to charge and discharge the energy. Its effectiveness depends on the melting-solidification cycle during the day. Other important properties of PCM roofing listed in Table 6 are thermal conductivity, specific heat capacity, density and optimum thickness. Thermal conductivity and volumetric heat capacity (i.e., a

product of specific heat and density) dictate how effectively PCM roof allow the heat to pass through the roofing layer, and optimum thickness controls the amount of heat flow for any particular PCM configuration.

A plot of the specific enthalpy (the sum of specific internal energy and pressure times specific volume) at various temperatures is

Table 6

Optical & thermophysical properties for various PCM materials installed in DOE benchmark built-up roof.

PCM material	Optical properties	k W/m/K	C J/kg/K	ρ kg/m ³	L kJ/kg	t_{opt} cm	Phase change temperature (°C)	Vendor/Source
BioPCM@M182Q21	$\epsilon = 0.9$, SR = 0.9, SRI = 114.4	0.2	1970	235	196	7.4	21–24	[39]
Enerciel 22		0.148	7085	832	177	0.3	18–29	[40]
Eutectic Salt ^a		0.54	1440	1640	188	0.63	26–28	[41]
Paraffin (C ₁₆ –C ₁₈)		0.148 [42]	534	775	152	0.33	21–24	[43]
CaCl ₂ ·6H ₂ O		0.6 [44]	1450	1050	160	1.62	28.5–30.2	[45]

^a Eutectic Salt = 48% CaCl₂ + 4.3%NaCl + 0.4%KCl + 47.3%H₂O.

Fig. 10. Enthalpy variation for different PCM with temperature.

shown in Fig. 10 for the various types of PCM materials evaluated. Here, the enthalpy illustrates a graphical representation of the phase change. Although there is a definite increase in enthalpy, the temperature remains relatively constant around 22 °C. The BioPCM@M182Q21 shows the most dramatic change in enthalpy of the materials, indicating the greatest capacity to store latent heat across a phase change.

3.2.1. Effects of different PCM as a roof internal layer

Different types of PCM were added as an internal roof layer, evaluated for the representative week and averaged over a 24 h interval. Again, the TRHG flux, surface temperature, and sensible heat flux were all considered. Fig. 11A specifically shows the TRHG flux effects of PCM materials within the envelope of the roof. Here, there is a significant difference between the BioPCM, $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ and the other PCM materials. BioPCM and $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ average TRHG flux during peak hours were 3.25 W/m^2 and 8.51 W/m^2 respectively, while all other PCM types were closer to 15 W/m^2 . This indicates that the use of BioPCM and $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ PCM types within the envelope of a roof could reduce the amount of energy consumption. The surface temperature and sensible heat flux shown in Fig. 11B and C reveal more agreement between the PCM types. BioPCM yields a maximum sensible heat flux value of 123.4 W/m^2 . Fig. 11D illustrates the TRHG flux across the seven representative cities. From this plot, it is clear that the Paraffin and Enerciel-22 yield the largest TRHG flux across the country. These results collectively indicate that both BioPCM and $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ PCM will serve to mitigate UHI by reducing energy demands through a reduction in TRHG flux, and $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ PCM also seems to contribute to UHI mitigation through reduced surface temperature and sensible heat flux.

Although the simulation results indicate paraffin generates a large TRHG flux, surface temperature, and sensible heat flux, it remains one of the more popular PCM material types used [46]. Paraffin has favorable properties as a building envelope material

Fig. 11. This image shows a sample of the simulation results for Miami, FL (A) sensible heat flux, (B) TRHG flux, (C) roof surface temperature, (D) and TRHG flux during average peak hours for seven major US cities for various PCM slab as a roof internal layer.

Fig. 12. Simulation results of Paraffin PCM layer in roof for different US cities for (A) roof surface temperature, (B) TRHG flux.

over other types, e.g., chemically stable, strong resistance to supercooling, non-corrosive, non-toxic, and high latent heat of fusion [18]. Also, paraffins are available in a broad range of melting temperatures, they are chemically inert, have low vapor pressure, and shows no indication of thermal performance degradation by thermal cycling. Thus, Paraffin was used for the rest of PCM analysis. Fig. 12 describes the effect of Paraffin within the roof envelope on the roof surface temperature and TRHG flux for each city is displayed over a 24 h period. Roof surface heat gain were chosen over sensible heat flux to compare the effect of heat flux on

different US cities since it was selected before to analyze the peak hours TRHG flux as shown in Fig. 11. These plots provide another vantage point with which to elucidate any subtle differences between climatic regions.

3.2.2. Effects of roof type with paraffin PCM slab as a roof internal layer

Various roof types combined with a slab of paraffin PCM inserted within the envelope of each roof were modeled and compared with one another over 24 h during the hottest week of the summer.

Fig. 13. This image shows a sample of the simulation results for Houston, TX (A) sensible heat flux, (B) TRHG flux, (C) roof surface temperature, (D) and TRHG flux during average peak hours for seven major US cities for various roof type with a paraffin PCM slab as a roof internal layer.

Again, TRHG flux, roof surface temperature, and sensible heat flux were considered, as well as the TRHG flux across climatic regions across the country. Fig. 13 shows the simulation results. TRHG flux is displayed in Fig. 13A. This plot clearly shows how well the asphalt shingle roof in combination with the paraffin reduces TRHG flux during peak hours. The built-up roof type was also notable in reducing the TRHG flux. The maximum TRHG flux for the asphalt and built-up roof types were 9.98 W/m^2 and 12.65 W/m^2 respectively. Unlike for cool roof where conduction plays a major role in TRHG flux values, in PCM roofing it's a rather complicated phenomenon which has contribution from conduction, convection, complex shapes of the phase change boundary and volume changes. According to our previous discussion in section 3.1.2 it can be deduced that metal roofs contribute the highest TRHG flux due to its superior thermal conductivity and diffusivity properties. The minimum TRHG flux is by asphalt shingle roofs due to its lowest thermal conductivity and diffusivity values. Since Paraffin was used as a PCM material for all different types of roofing materials, the simulation results for TRHG flux shows a similar pattern like cool roof results as shown in section 3.1.2.

Fig. 13B and C indicate little difference between each roof type for both the roof surface temperature and sensible heat flux. This phenomenon can be explained by similar optical properties for any particular roof type by keeping SR at 0.625 ± 1.5 and SRI at 74.5 ± 3.5 . Paraffin PCM has an almost negligible influence on either of those two parameters, roof surface temperature and sensible heat flux values.

Lastly, Fig. 13D illustrates the TRHG flux across each climatic region within the United States. Here, metal and concrete tile roof

types with paraffin PCM within the envelope of the roof illustrate the highest TRHG flux in each region, while the built-up roof and single ply membrane roof consistently show less TRHG flux than the metal and concrete tile roofs. The Asphalt roof has low values of peak TRHG flux, with small variation between the different regions. The combination of asphalt roof with a PCM layer would be an excellent choice for any region to reduce UHI effects. Depending on the location, the built-up roof or single ply membrane roofs, each with a PCM layer, could provide the best mitigation against UHI.

3.2.3. Effects of PCM slab location in roof

The effects of PCM at various depths within the envelope of the roof were evaluated. Fig. 14 contains the TRHG flux, roof surface temperature, and sensible heat flux for each depth (roof top, the innermost layer, and the middle layer). Fig. 14(A–C) all indicate little difference between any of the PCM locations. It is noticeable that when PCM placed as an innermost layer inside the roof it shows a slight increase of TRHG flux on peak hours during the day. Placing the PCM as an innermost layer could lead to higher energy expenditure by increasing the cooling load demand during peak hours. Simulation results displayed in Fig. 14D illustrate that this trend between PCM locations within the envelope is the same through the country. However, there are still clear differences in the TRHG flux across the different regions. It can be concluded that the location of a PCM layer within a roof envelope is not an important factor when considering UHI mitigation strategies. Other factors, such as air or water tightness, should be given priority over PCM depth.

Fig. 14. This image shows a sample of the simulation results for Chicago, IL (A) sensible heat flux, (B) TRHG flux, (C) roof surface temperature, (D) and TRHG flux during average peak hours for seven major US cities for various roof type with a PCM slab as a roof internal layer.

Fig. 15. This image shows a parametric analysis comparing cool roof (varying albedo with build up roof) and various PCM roof types for (A) TRHG flux, and (B) sensible heat flux across a range albedo values in Miami, FL.

3.3. Parametric analysis

The peak hours TRHG flux and sensible heat flux for various cool roofs and PCM roofs are analyzed in a comparative manner for all major US cities. In section 3.1.3 and 3.2.3 it was shown that insulation thickness variation and PCM slab location has negligible UHI contribution. For parametric analysis of cool roofs and PCM roofs, the main parameters chosen for potential UHI mitigation were albedo, roofing materials, and PCM types. This selection of primary UHI influencing parameters was based on the results of section 3.1.1, 3.1.2, 3.2.1, and 3.2.2.

3.3.1. Effects of albedo on PCM variation

A parametric analysis was performed to compare the sensible heat flux and TRHG flux computed from simulation results for cool roof with different albedo or solar reflectivity values and various PCM roof types. Fig. 15 clearly shows the significant differences between cool roof and PCM. The TRHG flux during peak hours for a variety of albedo values are displayed in Fig. 15A. The bar chart shows that cool roof technology yields a TRHG flux nearly twice as large as any of the PCM roof types. Since TRHG flux is directly related to energy saving measures, it could bring a huge relief to the building owners by reducing the energy bill. However to predict the economic benefit precisely for using the PCM roofs over cool roof, a detail comprehensive analysis will be needed. The same trend

occurs in Fig. 15B, where sensible heat flux values for cool roof technology are again found to be much larger than the competitive PCM roof types. Conclusively, this information illustrates the use of PCM within the envelope of a roof could potentially improve energy savings, and reduce UHI effects much more efficiently than cool roof technology. The PCM type that yielded the lowest TRHG flux during peak hours of a warm week of the summer was the BioPCM. The maximum TRHG flux was 6.32 W/m² at the low albedo value of 0.3. CaCl₂·6H₂O generated the least amount of sensible heat flux with a maximum of 150.9 W/m² at an albedo value of 0.3.

3.3.2. Effects of albedo on roofing materials

Another analysis comparing the effects of albedo on various roofing materials was performed. Fig. 16 illustrates the TRHG flux and sensible heat flux during peak hours for various albedo values. Both Fig. 16A and B indicate that the asphalt shingle roof type provided lower TRHG flux and sensible heat flux values across the range of albedo values. Thus, the use of an asphalt shingle roofs could provide an increase energy savings and a reduction in UHI effect. The maximum TRHG flux and sensible heat flux values for the asphalt roof type were 14.53 W/m² and 152.4 W/m² respectively. Fig. 16A shows that the differences between maximum and minimum peak hours TRHG flux for different roofing materials have much higher values for lower albedo roofing materials. It indicates that with the increase of roof surface albedo, the building

Fig. 16. This image shows a parametric analysis comparing various roof materials for (A) TRHG flux, and (B) sensible heat flux across a range of albedo values for Miami, FL.

will have much greater potential for lowering the energy cost for almost any types of building roofing materials. In particular, peak hours TRHG flux differences for different roof materials with albedo of 0.86, 0.7, 0.5, and 0.3 are 2.84 W/m², 10.1 W/m², 20.4 W/m², and 31.7 W/m² respectively. In Fig 16B peak hours sensible heat flux differences for different roofing materials also show similar results; the differences of sensible heat flux are reduced with the increase of roof surface albedo. Peak hours sensible heat flux differences for different roof materials with albedo of 0.86, 0.7, 0.5, and 0.3 are 14.6 W/m², 17.9 W/m², 29.5 W/m², and 48.7 W/m² respectively. It can be inferred from these findings that the increase of albedo in roofing materials have a smaller contribution to UHI mitigation.

4. Conclusions

Advancement in material technology for cool roof has been a continued effort throughout the world for mitigating the UHI effects. In addition to the surface properties, the materials enclosed within the roofs of buildings also play a large role towards mitigating UHI. PCM has been studied within the roof envelope along with the cool roof to help reduce energy consumption. Cool roof and PCM roof serve to improve UHI and energy performance by increasing the roof surface albedo and by storing latent heat of the roof materials respectively.

In this work a comparison of the two technologies was conducted. Cool roof materials and PCM were compared using performance parameters of roof surface temperature, thermal energy entering the enclosure via the roof, and sensible heat flux. Simulations were conducted over a range of climate zones across the United States. Multiple roof types and multiple PCM types were evaluated, and a parametric analysis was performed for the effects of albedo on PCM variations and roofing materials.

In general, with respect to reducing UHI effect, increasing albedo led to better performance. This study concluded that asphalt roofs tend to give the best results of all the roof types. Additionally, it was found that insulation did not play a significant role in the reduction of UHI effects. Ultimately, the PCM roof type proved its superiority to the cool roof technology with a maximum TRHG flux (i.e. heat flux to building interior through the roof) of 54% lower than the cool roof for various albedo. Similarly, the PCM roof technology showed a maximum sensible heat flux (i.e. heat flux from roof surface to the surrounding environment) of 40% lower than the cool roof technology for various albedo. Thus, it is clear that PCM roof technology is the future of energy-saving and heat island reducing rooftops.

Acknowledgments

The authors express their gratitude to the reviewers for their thoughtful feedback, which was used to improve the quality of the paper.

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