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A Review of Thermal Analysis on Novel Roofing Systems

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ABSTRACT

In this paper, we reviewed three types of novel roofing systems which can reduce building thermal loads: cool roof, green roof, and phase change material (PCM) roof. Cool roofs are designed to keep the roof cool by reflecting the incident solar radiation away from the building roof and radiating the stored heat away at night. Green roof, also called eco-roof, covered by vegetation, utilizes the thermal insulation provided by the soil and evapo-transpiration to keep the roof cool under the sun. PCM roofs employ phase change material with high latent heat of fusion in the roofs. PCM roofs are able to absorb large amount of heat at demand peak when PCM changes its phase, so that the heat from outdoor is stored in the PCM rather than flows into indoor space. The effort in the paper has compared the key parameters of each of the systems, thermal analysis methodologies, and the energy savings due to each of them with reference cases, in addition, we provide a comprehensive thermal analysis method applied in novel roof systems and a guide to design proper novel roofing system for a given climate and building types.

1. INTRODUCTION

In US, 41% of primary energy is consumed by the buildings sector so energy efficient building techniques have been emphasized in recent years, referring US Department of Energy 2011 buildings energy book. In addition to the active energy strategies which are operated through the performance improvements of heating, ventilation and air conditioning (HVAC) systems and lighting equipment, passive energy strategies through improvements on building envelope are considerably important. Research in building envelope technologies includes foundations, insulations, roofing and attics, and walls. As a major insulation role, roof varies significantly in heat transfer and thus building's energy use with different materials and structures.

Cool roofs are designed to keep the roof cool by reflecting the incident solar radiation away from the building and radiating the stored heat away at night. Light-colored coatings are generally used to deliver high solar reflectance and high thermal emissivity. The proven benefits of cool roofs are 1) saving energy consumption of cooling and improving indoor comfort, 2) mitigating the heat island phenomena effect in cities, 3) reducing maintenance cost by extension lifetime. Cool roofs are more and more utilized in practice. NYC °CoolRoofs is a promotion program in New York City, which has realized over 5 million ft^2 coated with reflective surface till now.

Figure 1 Volunteers painting an urban rooftop with a cool roof coating in the NYC °Cool Roofs Program (cool roof rating council)

Figure 2 Ford Motor Company's River Rouge Plant Green Roof (the greenroof & greenwall projects databse)

Green roof, also known as eco roof, is a rooftop covered by vegetation. Generally it is composed of vegetation layer, soil layer, webbing filter and drainage material, etc. According to the demand for maintenance and thickness of soil layer, green roofs can be categorized into intensive green roofs with regular maintenance and deep soil layers and extensive green roofs with thin soil layers and almost without maintenance. The evapo-transpiration of vegetation and insulation of roof layers lower the temperature at the roof level and thus reduce the heat flux to indoor environment. Besides, the benefits of green roof are not indicated in energy conservation but also aesthetic effects. The well-known applications of green roofs in US include headquarters of YouTube in San Bruno, Chicago Millennium Park, Ballard Library in Seattle, etc.

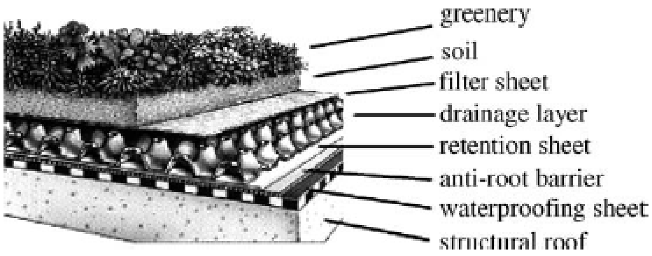

Figure 3 Layers of a green roof (Lazzarin et al. (2005))

PCM roofs employ phase change material with high latent heat of fusion in the roofs. They are able to absorb large amount of heat at cooling demand peak when PCM changes its phase from solid to liquid, providing a more consistent room temperature. Most PCM roofs are in the development stage to ensure kinetic and chemical safety besides proper thermodynamic properties such as specific heat, latent heat of fusion, melting temperature and volume change at phase transformation.

In this paper we summarize the thermal analysis methods used in the three novel roofs and compare the key parameters of each of the systems and the energy savings due to each of them through the review on recent literatures on thermal analysis and characteristics published after 2000.

2. COOL ROOF

In the application of cool roof, the key parameters include albedo, reflectance and emittance. Albedo is defined as the integrated specular and diffuse reflectance of solar radiation reaching the earth surface. The importance of albedo in cool roof materials has been demonstrated in many studies. For instance, Prado et al. (2005) experimentally studied the albedo of different building roof materials including ceramics, metals and cement with various colors. This study experimentally showed the red and white ceramics which have a higher albedo than fibrocement have the lower temperatures than surroundings and that cool surfaces with raised albedo and emittance are viable and low-cost.

Thermal analysis can be performed conveniently in building energy simulation softwares, such as EnergyPlus, TRNSYS, eQuest, etc. Akbari el al. (2005) used calibrated DOE-2 simulation to extrapolate savings for three types of one-story commercial building in 16 different California climates. In a wider geological range, Synnefa et al. (2007) simulated the use of cool and cool colored materials on the residential energy load for 27 cities around the world representing different climatic conditions in TRNSYS. Jo et al. (2010) analyzed the cost benefit and indirect benefits by comparing three different cases in EnergyPlus: baseline before cool roof construction, half of the roof with cool roof material and full cool roof installation.

There are also a great amount of experimental studies on characteristics of cool roof. Akbari et al. (2005) collected data of six buildings in California. Their monitor objectives include: the temperature at the roof surface and indoor roof surface at the same location for at least three locations, the indoor and outdoor temperatures, the outdoor relative humidity, wind speed, insolation, and the air-conditioning and total-building electricity uses, and heat flux. Prado et al. (2005) measured the spectral characteristics of most popular cool roof materials in Brazil: red and white ceramics, fibrocement without asbestos, coated and uncoated aluminum and stainless steel, aluminum and zinc coated metal, thermal-acoustic metal that can be aluminum, green, white and ceramics in color, and colored cement.

Synnefa et al. (2006) measured the surface temperatures of 14 reflective materials in daytime and during night. Levinson et al. (2007) compared six colors with scale houses located in California. Jo et al. (2010) tested temperatures and albedo of white-colored roof in full-scale building in Phoenix.

To quantify the benefits via application of cool roof, Akbari et al. (2005) reported that cool roof could bring about to up to \$2.0/m^2 in the value of total annual air conditioning savings for one-story commercial building. Synnefa et al. (2007) reported 4°C and 2°C during the day and night respectively lower than the ambient in hot condition when white concrete tile is used in Greece. They also indicated the two major factors affecting the energy savings due to cool roof to be climate condition and roof U-value through parametric analysis. Jo et al. (2010) reported 18% electricity saving in Phoenix.

Table 1 Summarization of recent studies on cool roof

	Location	Roof color	Experiments	Simulation	Key parameter	Conclusion
Akbari et al. (2005)	California	Gray	6 buildings	calibrated DOE-2	Reflectance	up to \$2.0/m^2 in the value of total annual air conditioning savings
Prado et al. (2005)	Brazil	Red, white, etc.	spectral characteristics measurement	N/A	Albedo	lower surrounding temperatures and cooler surfaces with raised albedo
Synnefa et al. (2006)	Greece	Silver, white	14 types of sample	N/A	Spectral reflectance, the infrared emittance	Reflectance dominates in daytime while emissivity does during night.
Levinson et al. (2007)	California	terracotta, chocolate, gray, green, blue, black	Scale houses	N/A	Emittance, reflectance	Statewide peak cooling reduction: 240MW, annual cooling saving: 63GWh/yr, annual emissions: 35 ton CO2, 1.1 ton NOx, and 0.86 ton SOx
Synnefa et al. (2007)	World wide	N/A	N/A	TRNSYS	Reflectance, U-value	Heating penalty is much less than cooling load reduction.
Jo et al. (2010)	Phoenix	White	Full scale	EnergyPlus	Albedo	Electricity saving up to 18%
Uemoto et al. (2010)	Brazil	White, brown, yellow	UV/VIS/NIR reflectance measured	N/A	Reflectance	Cool colored pigments produce significantly higher NIR reflectance and lower surface temperature by 10°C.

The above mentioned and other studies are summarized in Table 1, from which it can be found that a great amount of experimental research on cool roof. Most simulations are performed in building energy modeling software. The savings in energy, economy and emissions are proven to be reduced.

3. GREEN ROOF

Compared to cool roof, green roof is more complicated to perform thermal analysis both in modeling and experiments since a greater amount of properties are involved. The properties related to evapo-transpiration, such as vegetation type, leaf area index (LAI) and thickness of soil layer, are generally viewed as the key parameter. LAI is defined as the ratio of area of leaves to the area of the base occupied. Kumar et al. (2005) investigated the effects of

LAI on canopy air temperature and heat flux and concluded larger LAI reduces the canopy air temperature, stabilized the fluctuating values and reduced the penetrating flux by nearly 4W/m^2.

The simulation studies on the green roof apply more numerical modeling based on heat transfer and thermodynamics principles than energy simulation software. Kumar et al. (2005) utilized a control volume approach based on finite difference methods to analyze layer components which was coupled into building simulation codes when got validated. Lazzarin et al. (2005) also developed a numerical model and compared the modeling prediction with experimental results, in which the evapo-transpiration effect was quantified by a semi-empirical approach proven to be satisfactory in wet conditions. Zinzi et al. (2012) presented a numerical comparative analysis between cool and green roofs by dynamic simulations, mainly focusing on locations at Mediterranean latitudes, with Design Builder and EnergyPlus.

There are also experimental studies performed widely, most of which are used to validate the model due to the complexity of varying input parameters. Kumar et al. (2005) performed experiments to validate the modeling prediction of canopy air temperature and indoor air temperature. Liu et al. (2003) performed an experimental study which lasted two years in Ottawa. Sailor (2008) developed a green roof module based on models of heat and moisture exchange. The module has been implemented in EnergyPlus.

To quantify the benefits brought about by green roof, Kumar et al. (2005) reported that average indoor air temperature was reduced by 5°C, and that a cooling potential of 3 kWh per day at leaf area index (LAI) of 4was provided based on a single room occupied by four people. Liu et al. (2003) reported 40°C decrease in the temperature of exposed roof membrane, 39°C decrease in temperature fluctuation and 75% decrease in heat flux. Lazzarin et al. (2005) concluded that in summer the heat flows in through green roof with dry soil is about 60% compared to traditional roofing with an insulating layer due to the higher solar reflection and absorption of the greenery. In a wet condition, not only the entering flux is cancelled, but a slight outgoing flux is produced so that the green roof works as a passive cooler due to the cooling effects of evapo-transpiration which is shown in Figure 4.

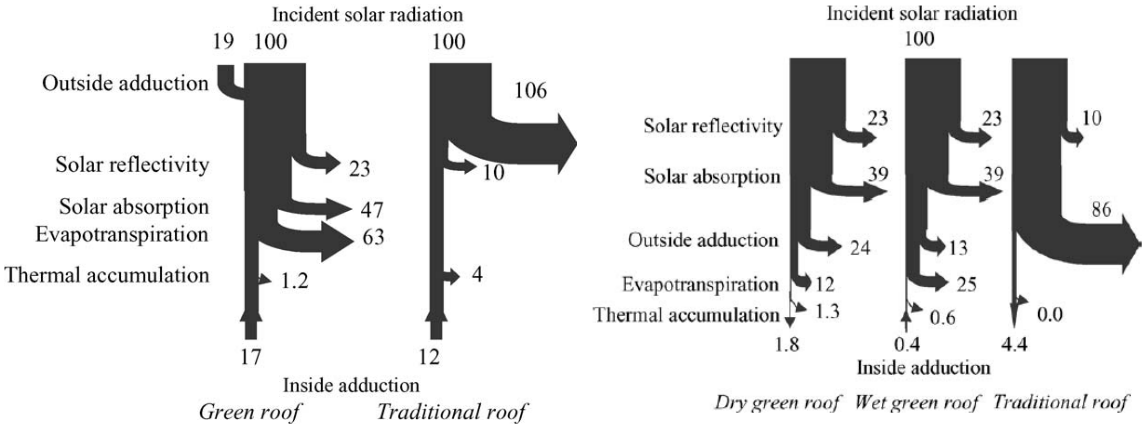

Figure 4 Comparison of the energetic exchanges of green roof with a traditional roof, winter and summer (Lazzarin et al. (2005))

The above and other studies are summarized in Table 2. Different from cool roofs, the model-based research are more emphasized for green roofs and numerical modeling methods utilized in more situations on roofing systems instead of building-level energy simulation.

Table 2 Summarization of recent studies on green roof

	Location	Vegetation	Experiments	Simulation	Key parameter	Conclusion
Liu et al. (2003)	Ottawa	wild flower meadow	2-year	N/A	N/A	75% decrease in heat flux through roofing system

Kumar et al. (2005)	India	N/A	Validating canopy temperature	Numerical	LAI	3 kWh cooling capacity per day
Lazzarin et al. (2005)	Greece	N/A	Summer, winter	Numerical	Latent flux	Wet green roof in summer can even result in an outgoing flux.
Santamouris et al. (2007)	Greece	Local wild plants	Two stories	TRNSYS	N/A	Significant reduction in cooling load, no important impacts on heating load.
Sailor (2008)	Chicago, Houston	N/A	Two stories	FASST vegetation model integrated in EnergyPlus	Soil thickness, LAI, and irrigation.	The model is applicable.
Parizotto et al. (2011)	Brazil	Bulbine frutescens	Compared with ceramic and metallic tiles	N/A	Climate condition	Cooling capacity of green roof is reduced in high relative humidity climate.
Zinzi et al. (2012)	Mediterranean	N/A	N/A	Numerical	N/A	Green roof is less effective than cool roof.

The most numerical models are based on one dimensional transient heat transfer principles in Incropera et al. (2002). They incorporate typical meteorological year (TMY) data or other climatic data as the inputs to predict the temperature distribution, heat transfer rate, energy storage, etc at a desired time step such as one hour. Finite methods are employed in the numerical calculation mostly. The calculation domain is the thickness of roof system with the outdoor boundary as the origin. For example, finite difference method (FDM) is utilized to discretize the original continuous time-space domain into finite discrete nodes and to substitute the discrete temperature values at each node in the new domain for the continuous temperature distribution over the original domain by solving the discretization equations characterizing the numerical relation among nodes. The general model execution follows the flow chart in Figure 5.

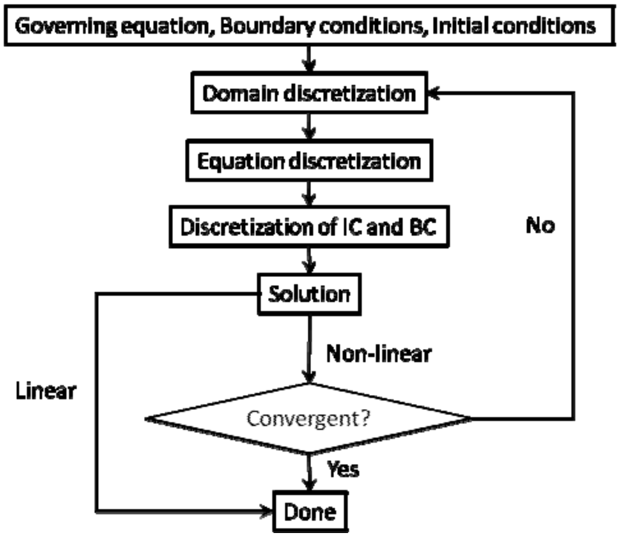

Figure 5 Flow chart of model execution

The general assumptions made in the models include:

1. The end effects can be neglected.
2. Constant thermal properties including conductivity, density and specific heat.
3. Perfect thermal contact between layers.

The outside surface is exposed to solar radiation (I_s), convection ($q_{conv,o}$) and radiation exchange with the sky (q_r). The solar radiation could employ the ground horizontal irradiance (GHI) in TMY data, indicated in **Error! Reference source not found.**.

$$I_s = GHI \tag{1}$$

Convective heat transfer coefficient is mainly determined by the wind speed V, and its calculation follows an empirical expression **Error! Reference source not found.** by Goswami et al. (2000),

$$h_o = 3.8 * V + 5.7 \tag{2}$$

The radiation exchange with sky is calculated by **Error! Reference source not found.**

$$q_r = \varepsilon_o \sigma (T_{sky}^4 - T_{x=0}^4), \tag{3}$$

Where $\varepsilon_o$is the outdoor emissivity, σ is the Stefan-Boltzmann constant, and the sky temperature can be calculated by the empirical equation by Duffie et al. (2013)

$$T_{sky} = (T_o + 273)(0.711 + 0.0056T_{dp} + 0.000073{T_{dp}}^2 + 0.013cos(15\frac{t}{3600}))^{0.25} \tag{4}$$

The boundary condition at outer surface is given by

$$k\frac{\partial T}{\partial x}|_{x=0} = \alpha I_s - q_r - h_o(T_{x=0} - T_o) \tag{5}$$

where α is absorptivity of the surface.

The governing equation for 1D transient heat transfer for one layer with thickness of Δx between the outer and inner surfaces is

$$\frac{\partial T}{\partial t} = \alpha\frac{\partial^2 T}{\partial x^2} \tag{6}$$

The overall heat transfer networks are indicated in Figure . In the case of green roof, the energy balance is complicated by the heat interactions between foliage layer and others in Figure 7.

4. PCM

In previous research, most applications of PCMs in buildings are located in wallboard while those located in roof is relatively rare. The determinants of PCMs application are melting temperature and phase change enthalpy, in addition to chemical stability, fire characteristics and compatibility with construction materials. In the situation of buildings, the PCMs with a phase change temperature of 18–30°C are preferred, including organic PCMs, salt hydrates and eutectics, as well as commercial PCMs. The thermal analysis method used for PCM roof is mostly based on numerical method as is used for green roof. However, due to the various geometry of PCM containers, the model is developed into three dimensions in most studies.

Alawadhi et al. (2011) employed pre-conditional generalized minimum residual solver to solve a three-dimensional heat transfer model across the roof with holes filled with PCM by comparing the heat flux at the indoor surface and proved that the PCM-roof acted well as the cool roof. In this research, different materials and geometries of the

PCM container were compared, results of which indicated 39% reduction in heat flux can be achieved by using n-Eicosane as PCM in the conical container.

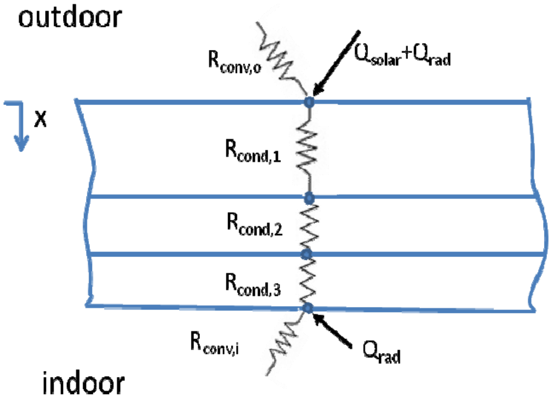

Figure 6 Overall thermal resistance graph

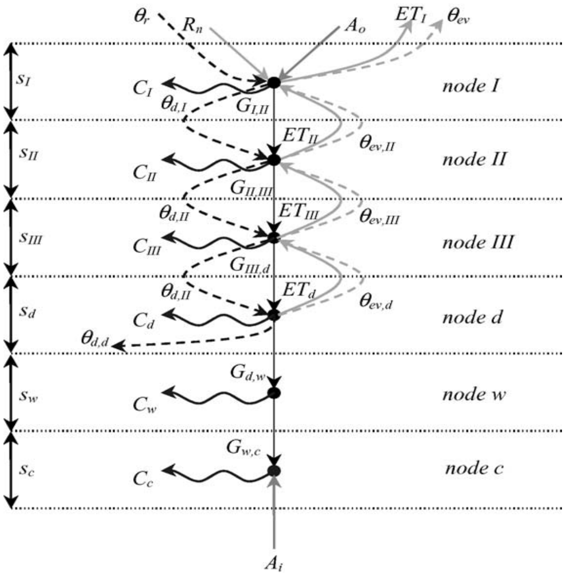

Figure 7 The finite differences model of physical system (Lazzarin (2005))

Since one layer PCM roof is limited to cold or hot weather, Pasupathy et al. (2008) investigated a double layer PCM with both experiments and numerical simulation. The semi-implicit method was used in simulation with time step of 2s and system equations were solved by tridiagonal matrix algorithm. In experiments, two test rooms were built to compare the temperatures at roof top, ceiling and indoor ambient with and without PCM-roof. With the validated model, two-layer PMC roof was simulated. The results indicated that a double layer PCM roof is more possible to provide a constantly comfortable temperature all the time in one day and over various seasons.

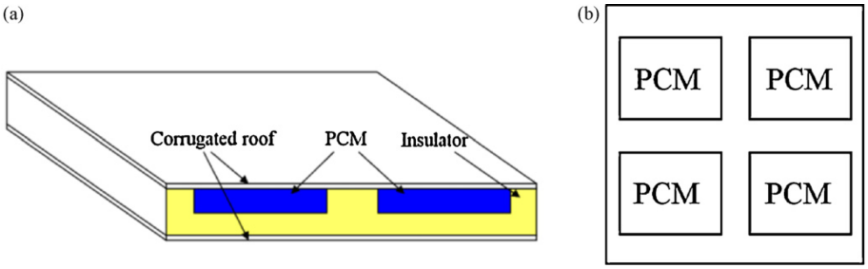

Figure 8 Novel design structure of the corrugated roofing. (a) 3D view; (b) Top view (Chou et al. (2013))

The above and other studies are summarized in Table 3.

Table 3 Summarization of recent studies on PCM roof

	Location	Material	Experiments	Simulation	Key parameter	Conclusion
Saman et al. (2005)	N/A	$CaCl_2{\cdot}6H_2O$	Flat Slab	2D enthalpy formulation model	N/A	The effects of sensible heat, inlet air temperature and air flow on

						freezing and melting were analyzed.
Pasupathy et al. (2008)	India	inorganic salt hydrate	Slab	1D numerical model	Melting temperature and climate	Double layer PCM roof is more possible to provide a constantly comfortable temperature all the time in one day and over various seasons.
Alawadhi et al. (2011)	N/A	n-Octadecane, n-Eicosane, and SUNTECH	N/A	3D numerical model	Geometry	39% reduction in heat flux can be achieved by using n-Eicosane as PCM in the conical container.
Alqallaf et al. (2013)	Kuwait	A28, A32, and A38	vertical cylindrical holes	3D finite element method	Dimension of cylinder, melting point	Heat gain can be reduced more with larger PCM holes diameter. The PCM melting temperature of PCM should be selected based on the operating month and working hour period during the day.
Chou et al. (2013)	Taiwan	N/A	Corrugated	1D numerical model	Amount of PCM	The new design (Figure 8) is helpful in reducing the downward heat flux.

CONCLUSION

In this paper, previous research work since 2000 on thermal analysis of cool roof, green roof and PCM roof have been reviewed. As a most cost-effective roof technology, cool roof has been widely studied and used with various proven strengths. The key parameter that should be taken into consideration in roof design is the reflective property of cool material, based on which, a high emittance can give extra benefits. The melting point and latent heat are the most important parameters for PCM roof while LAI and soil condition are most important for green roof.

Both modeling and experimental studies are performed widely in cool roof and building energy simulation software is used the most. Different from cool roof, the studies on green roof require more input variables and assumptions, so experimental results are mostly used for validation while numerical modeling, which has been summarized in this paper, is required to meet the needs of varying inputs. The analysis of PCM roof is similar to green roof but extended to three dimensions due to the different container geometry.

NOMENCLATURE

BC	boundary condition	
FDM	finite difference method	
GHI	ground horizontal irradiance	W/m^2
h	convective heat transfer coefficient	W/m^2-K
I	solar radiation	W/m^2
IC	initial condition	
k	conductivity	W/m^2-K
LAI	leaf area index	(-)
V	wind speed	m/s
PCM	phase change material	
q	heat flux	W/m^2
T	temperature	K
TMY	typical meteorological year	
t	time	s
α	absorptivity	(-)
ε	emissivity	(-)
σ	Stefan-Boltzmann constant	kg s^{-3} K^{-4}

subscripts

i	indoor
o	outdoor
s	solar

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