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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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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 cool roof and PCM (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.

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-Tetrolymer 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
Gr_{L_n}	Grashof number, $g\rho^2 L_n^3 \Delta T / T_f \mu^2$
g	gravitational constant
h_r	heat transfer coefficient
k	conductivity of air
L_n	characteristic length for natural convection, (area-to-perimeter ratio)
Nu	Nusselt number
Pr	Prandtl number
$q_{r,s}$	sensible heat flux
$q_{r,g}$	through roof heat gains flux
Ra	Rayleigh number
Re_x	Reynolds number
R_f	surface roughness factor
T_a	outside air dew-point temperature
T_f	roof surface film temperature—average of roof temperature and outside air temperature
T_r	roof outside surface temperature
x	distance along wind direction from roof edge to convection coefficient evaluation point
x_c	critical length
u	free-stream wind speed at roof level
ΔT	roof outside surface temperature minus outside air temperature
β	weighting factor for natural convection
μ	viscosity of air evaluated at T_f
ρ	density of air evaluated at T_f
ε	emissivity
HVAC	heating, ventilation, and air conditioning
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, CaCl.6H$_2$0, 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 [47]. 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