Estimates of cooling effect and energy savings for a cool white coating used on the roof of scale model buildings

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Estimates of cooling effect and energy savings for a cool white coating used on the roof of scale model buildings

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Abstract. The solar reflectance and thermal emittance of uninsulated scale model buildings in Beijing were measured in the laboratory and the actual outdoor environment. The solar reflectance index (SRI), roof surface temperature and energy savings were estimated using DOE roof saving calculator. The roof albedo measured in the field tests is independent of the inverted pyranometer height. A 0.493 increase in solar reflectance (laboratory measurements) yields SRI increase by 67.5, roof surface temperature reduction by 25.5 °C, annual peak demand reduction by 0.1 $kWm^{-2}yr^{-1}$, and annual net energy savings by 6.8 $kWhm^{-2}yr^{-1}$, while a 0.459 increase in roof albedo (laboratory measurements) generates SRI increase by 62.3, roof surface temperature reduction by 23.5 °C, annual peak demand reduction by 0.1 $kWm^{-2}yr^{-1}$, and annual net energy savings by 6.4 $kWhm^{-2}yr^{-1}$. At the city scale, these savings would reduce emissions from China's power plants by 60 kton CO_2, 1.1 kton NOx, 2.1 kton SO_2 and 19.4 kton carbon dust for the laboratory tests and by 56.6 kton CO_2, 1.0 kton NOx, 2.0 kton SO_2 and 18.3 kton carbon dust for the field tests.

1. Introduction

The urban heat island (UHI) is an environmental problem, which is considered to be a heating process in urban areas, resulting in the overall temperature of urban areas higher than the surrounding rural areas [1]. High temperature, high energy consumption, high air conditioning refrigeration demand, and environmental pollution have been listed as several direct factors of UHI [2, 3]. Therefore, many studies related to the application of high reflectivity materials as cool-pavement technology or cooling coatings have attracted people's interest [4-8]. Cool roof coatings have been demonstrated to be inexpensive materials that can effectively reduce the solar heat gain of buildings [9]. Thus, in summer, at the building scale, use of cool roof coatings can lower the surface temperature of buildings, cut down air-conditioning cooling load and electrical use and improve thermal comfort and indoor air quality [9, 10]. At the city scale, widespread of cool materials may minimize urban air temperatures, slow the smog formation and mitigate urban heat islands [11-13].

In the United States, many simulation studies have estimated the effects of cool roof coatings on the cooling energy saving, the peak cooling power demand, and the reduction of CO_2 emissions annually. The simulated ceiling and wall thermal resistances were 5.28 and 3.35 m^2KW^{-1} respectively [14]. The similar simulation results were obtained for a flat concrete roof on a simple single room building [15]. Extrapolating the savings to the entire state, the estimated statewide peak cooling power and annual cooling energy savings would be 240MW and 63GWh, respectively, reducing annual emissions by 35 kton CO_2, 1.1 ton NO_x, and 0.86 ton So_x [12].

Outside the United States, simulation studies have also documented the energy savings. When a roof albedo increased from 0 to 1, in mild climate of Jordan, the simulated total energy load decreased by 32% and 26% for uninsulated buildings and insulated buildings, respectively; while in hot climate of Jordan, the total energy load reduced by 47% and 32% for uninsulated buildings and insulated buildings, respectively [16-18]. A 30% increase in roof albedo could achieve 12% annual cooling energy saving in Hong Kong [19]. Large scale use of cool roofs in Andalusia, Spain, could potentially save 0. 295 $GWhyr^{-1}$, reducing annual CO_2 emissions by 136,000 metric tons [20].

Note that energy consumption and peak demand savings with cool roof coatings strongly depend on climatic conditions [21-23], the amount of roof insulation installed [11, 22], the roof albedo and thermal emittance [22]. The largest potential for energy savings was always found to be associated with uninsulated roof assemblies or buildings with excessive attic air infiltration [11, 22]. In addition, although energy saving potential has received considerable attention in the United States and a few investigations on this topic has been carried out in Europe, there is nearly no such studies in the mainland of China. Therefore, regardless of the above mentioned extensive simulation studies, it has very important theoretical and practical significance to do the similar research work in Beijing.

Thus, four adjacent scale-model buildings were built in Beijing to evaluate the roof albedo, roof thermal emittance, ceiling heat flux and energy savings. To this purpose, roofs of two model buildings were painted with a self-developed cool white coating, whose optical, thermal, physicochemical properties were described in detail somewhere else [24-27]. In the current study, the structure of the model buildings is described in detail. The albedo and thermal emittance of the painted and unpainted roofs were measured in the laboratory and field; the thermal resistance of the roofs was evaluated. The obtained data are then used to estimate the cooling effect, the annual peak demand and cooling energy savings, the heating penalty, the net energy savings and the reduction of emissions. In addition, the cooling effect and the annual cooling energy savings estimated from filed tests are compared with those computed from laboratory measurements.

2. Methodology

2.1. Experimental Work

This study was performed using four identical scale model single story buildings (referred to as Buildings 1, 2, 3 and 4) set on temporary concrete footers and located at the Technical Center, China State Construction Engineering Co., Ltd., Beijing. Each model building was constructed of a 2.0 m long × 2.0 m wide × 3.0 m high pre-fabricated concrete structure with one access door (Figure 1). The walls and roofs of the buildings consisted of 12.5 cm and 15 cm thick concrete, respectively. Because rooftops in China are typically flat and in some areas roofs have little or no insulation, the flat roofs of the model buildings were not insulated. Furthermore, to isolate the effect of cool roof coatings on cooling energy savings, all the model buildings were designed to have no windows. In addition, to provide each model building's roof with full southern solar exposure free from shading by surrounding structures and neighboring scale models [12], side-by-side model buildings were oriented to align the ridge of its roof along an south–north line. The doors (2.0 m long × 2.0 m wide) of the buildings with high thermal insulation faced north.

A cool white coating, developed in our laboratory, was airlessly sprayed onto the roofs of the buildings 1 and 3 as control sites, respectively; the buildings 2 and 4 were left unchanged as reference buildings (as the base case). The buildings 1 and 2 were installed with air conditioners, allowing a comparison of the energy use of the two buildings to determine energy savings, while the buildings 3 and 4, left in their initial condition (without air conditioners), were used to evaluate the net cooling effect resulted from use of the cool roof coating.

Figure 1. Four identical scale model buildings situated at the Technical Center, China State Construction Engineering Co., Ltd., Beijing. From the close-by examples (south) to those far off (north), the four buildings are a non-air-conditioned house with an unpainted grey roof and walls, an air-conditioned house with an unpainted grey roof and walls, an air-conditioned house with a painted white roof and unpainted walls and a non-air-conditioned house with a painted white roof and walls. A weather tower stands in the surrounding grasses.

2.2. Estimation of Cooling Effect and Energy Consumption

Solar reflectance (roof albedo) and thermal emittance are two key factors affecting roof surface and near-surface ambient air temperature. Once the incident solar radiation strikes an illuminated opaque roof surface, a fraction of the radiation is reflected, and the other fraction is absorbed as heat. A fraction of the absorbed energy penetrates into the building, a fraction is convected to air (rising air temperatures), and the remaining is radiated to the sky [28]. The high solar reflectance decreases solar heating, and the high infrared emittance enhances radiative cooling [29]. For equivalent solar reflectance, a lower emissivity of a surface leads to a higher steady-state temperature [22, 28]. Apparently, a cool roof material should have both high solar reflectance and high thermal emittance [30]. Incorporating both solar reflectance and thermal emittance in a single value yields solar reflectance index (SRI), a metric of the surface’s ability to reject heat. This composite measure quantifies how cool a surface would become relative to a standard black (solar reflectance 0.05, emittance 0.90, SRI = 0) and a standard white surface (solar reflectance 0.05, emittance 0.90, SRI = 100) [30]. The higher the SRI of a surface is, the lower its steady-state temperature is.

Thus, the cooling effect of the cool white roof coating is generally characterized with solar reflectance index (SRI) and roof surface temperature, which can be quickly and accurately computed using solar reflectance index calculator under standard conditions specified by ASTM (American Society of Testing Materials) E 1980-11. Several SRI calculators yielding the same results have been developed and available on line [31-33]. Because the prototypic houses for simulations have horizontal opaque roof surfaces, the cooling effect of the cool roof coating is assessed using SRI calculator coded by Ronnen Levinson, Heat Island Group, Lawrence Berkeley Laboratory [31].

Of the available cool roof simulations to estimate cool roof savings, the most commonly used online DOE Cool Roof Calculator [34] computations have no interaction with the characteristics of the building and thus avoid the confounding building variables that may confuse testing the performance of a roof [35]. The calculator was based on a simplified model [36] correlating the cooling energy savings and heating penalty to annual cooling degree days (base 18 ºC, CDD18) and heating degree days (base 18 ºC, HDD18). It was further adapted by Petrie et al. [37]. This online tool estimates cooling and heating savings for flat and/or low slope roofs with non-black surfaces relative to a black roof as a function of solar reflectance, thermal emittance, roof thermal resistance, cooling and heating equipments, as well as climate.

According to ASTM E903-96, a UV/VIS/NIR spectrophotometer (Perkin Elmer Lambda 750) equipped with an integrating sphere (150 mm diameter, Labsphere RSA-PE-19) was used to measure the spectral reflectance of the coating in the wavelength range between 250 to 2500 nm. The solar reflectance was computed by integrating the measured spectral data weighted with the air mass 1.5 beam-normal solar spectral irradiance described in ASTM E891-87 (Tables for terrestrial direct normal solar spectral irradiance for air mass 1.5) (hereafter, E891 BN).

Two double-dome pyranometers (JTR05, Beijing JT Technology) with a resolution of 1W /m^2 were used to measure albedo for ground, painted and unpainted roofs. The diameter of the sensor is 17.5 cm. The analog output from the pyranometer was converted to digital output with a readout meter that can be directly connected to PC via mini-USB cable for quick data download and PC control.

In the field tests of roof albedo, one pyranometer was used to measure incident solar irradiance I_i by facing its sensor directly away from the target roof surface; simultaneously, the other was positioned at the center of the roofs to measure reflected solar irradiance I_r by facing its sensor directly toward the target roof surface [11, 22, 38, 39]. According to ASTM E1918-06 (Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field), the measured roof albedo $R_{measured}$ may then be evaluated by:

$$R_{measured} = \frac{I_i}{I_r} \tag{1}$$

When the pyranometer is inverted and faces toward the target roof surface, the effects of the sensor-to-surface view factor on the measured roof albedo should be considered [39, 40]. The view factor F_{12} is defined as the fraction of energy exiting an isothermal, opaque, and diffuse surface 1 that directly impinges on surface 2 [39]. The view factor underestimates the true albedo of the surface and need to be used to correct the measured albedo. With the pyranometer being moved further from the surface, it becomes subject to environmental radiation, particularly if the surface is small [40]. The measured roof albedo should be corrected using view factor algebra.

For a disc of radius R_1 (sensor) to a coaxial parallel disc of radius R_2 (incircle of the square roofs) at separation H, the sensor-to-surface view factor F_{12}' may be computed by:

$$F_{12} = \frac{x-y}{2} \tag{2}$$

with

$$x = 1 + 1/r_1^2 + r_2^2/r_1^2 \tag{3}$$

and

$$y = \sqrt{x^2 - 4r_2^2/r_1^2} \tag{4}$$

where $r_1 = R_1 / H$ and $r_2 = R_2 / H$ [41]. Ground albedo (a_{ground}) may be determined directly from measured values, because the ground can be considered as an infinite plane [22]. The true roof albedo may be corrected by:

$$a_{roof} = 1/F_{12}[a_{measured} - (1 - F_{12})a_{ground}] \tag{5}$$

The above corrected roof albedo is actually clear sky air mass one global horizontal (AM1GH) solar reflectance, which can more accurately predict solar heat gain and thus obtain more accurate simulation results [42]. The total hemispherical emittance was measured using a portable differential thermopile emissometer AE1(Devices & Services Co., Dallas, TX) according to ASTM C 1371. The device contains a heater to maintain the temperature of the detector. The instrument is calibrated using a high emittance standard and a low emittance standard placed on the flat surface of a heat sink. The emittance of the test specimen is determined by comparison to the emittances of the standards.

3. Results and discussion

3.1. Solar reflectance and thermal emittance of the roofs

As mentioned earlier, albedo (or solar reflectance) and thermal emittance of a roof are two key metrics that need to be measured to estimate roof surface temperature reduction and energy savings due to the use of cool coating. As described in section 3, solar reflectance of materials can be measured either by a spectrophotometer in a laboratory or by a pyranometer in the field. Both results are presented below.

Ordinary concrete in the same grade as the walls and roofs of the model buildings was used to prepare the samples and substrates (2×2×2 m). The cool white coating, manufactured in our lab, was airlessly sprayed onto three concrete substrates (designated as S-1, S-2 and S-3). The coating thickness, measured by a PosiTector 200-Ultrasonic coating thickness gauge, was 200 ± 10 nm. The obtained spectral reflectance curves are shown in Figure 2. As shown in Figure 2, the spectral reflectance curves for samples S-1, S-2 and S-3 nearly overlap over the solar spectrum (Figure 2a). In the UV (ultraviolet) region, the coating samples show stronger absorption than the ordinary concrete sample, while in the VIS (visible) region and the NIR (near-infrared) region, the coating samples display much stronger reflectance. The average solar reflectance of the coating samples and measured solar reflectance of the concrete are approximately 0.889 and 0.396, respectively.

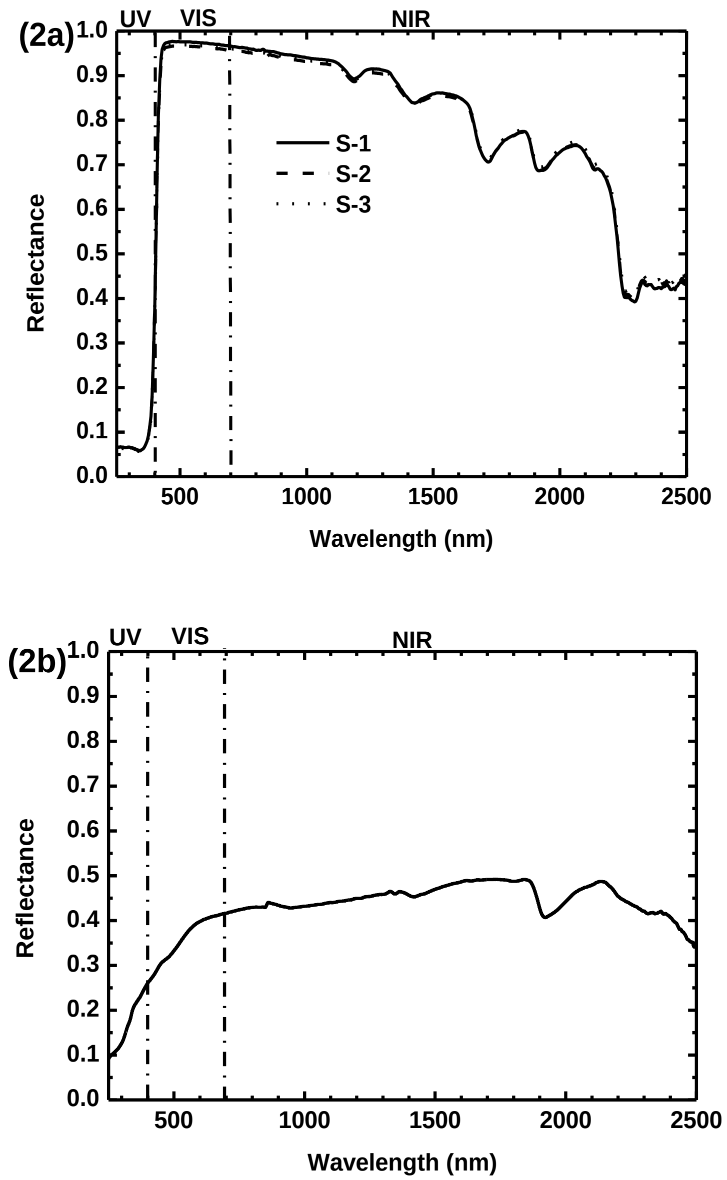

Figure 2. Spectral reflectance curves for (a) three samples of the cool white coating painted on the roofs of the model buildings and (b) the concrete.

In order to measure the roof albedo in the actual outdoor environment, two clear and calm days were deliberately selected (Figure 3). The measurements were carried out between 10:00 to 14: 00 local standard time (Beijing time) on September 20 and 21 (the autumn equinox), a daily time window during which the solar zenith angle $z \leq 45$ °C [39]. As shown in Figure 3, the incident solar irradiance and reflected irradiance were simultaneously measured by a facing up pyranometer on a fixed tripod and an inverted pyranometer hung from an end of a stand. In the latter case, the effects of the stand's shadow on the measured results could be minimized or eliminated.


Figure 3. Photos for field tests of ground albedo and roof albedos on two clear calm days (September 20 and 21, 2013).

To correct the measured roof albedo, the albedo of the grasses surrounding the model buildings was first measured at 10: 00 am on September 20, 2013 and the obtained results, along with a linear regression fit to the data, are plotted in Figure 4. Figure 4 shows that the albedo of the grass is independence of time. The measured albedo of the grass is 0.196, which is in good agreement with the albedo of 2" long, dry, moderate green grass reported by Taha and coworkers [40].

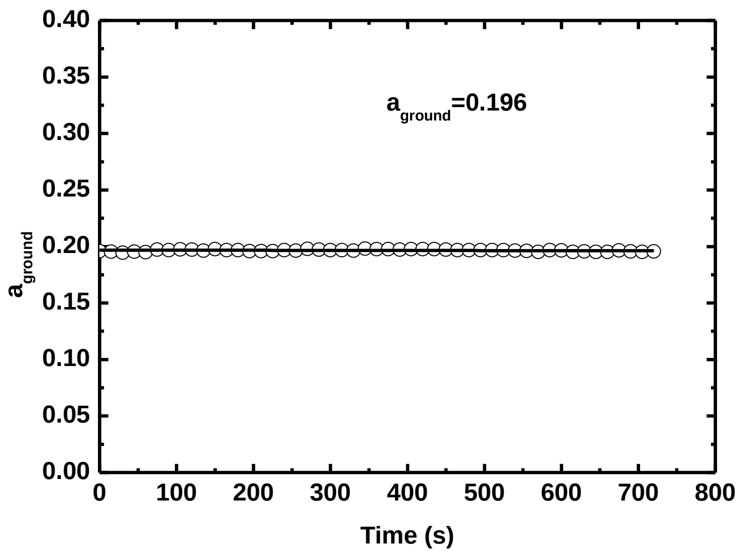

Figure 4. Solar reflectance of the grass surrounding the model buildings measured in the field at noon on September 21, 2013. The solid line is a regression fit to the data.

The time dependence of the measured and corrected roof albedos, together with the corresponding linear regressions, is presented in Figure 5. The pyranometer height for the measurement was 40 cm. The measured roof albedo was corrected using equation 5. As expected, during the measuring time windows when the solar zenith angle $z \leq 45$ °C, the measured roof albedo and subsequently corrected roof albedo (true albedo) are independent on time. This observation is consistent with what reported by Taha et al [40]. The gravel albedo was found not to vary with solar angle or altitude. In other words, the measured gravel albedo was independent of measuring time [40].

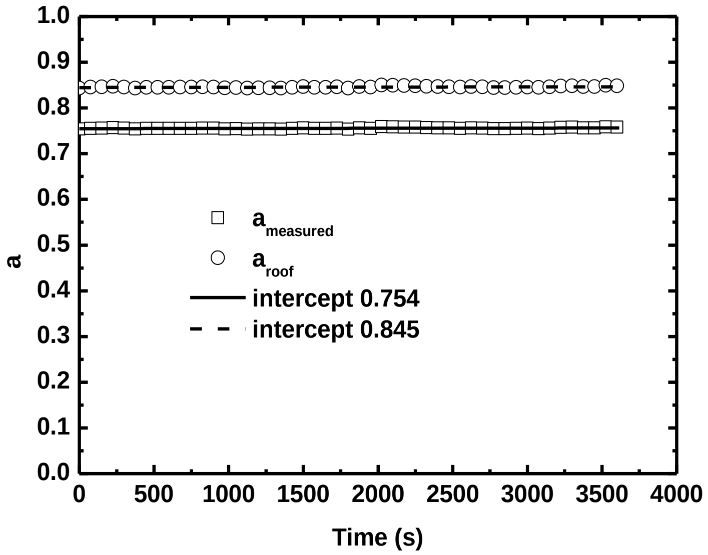

Figure 5. Time dependence of the albedo for a roof painted with a cool white coating measured on September 21, 2013. The open squares represent the roof albedo directly measured in the field. The open circles represent the roof albedo corrected using equation 5. The solid and dashed lines are regressions fit to the data.

The time dependence of albedos of a roof painted with the cool white coating directly measured at different inverted pyranometer heights are compared in Figure 6a. Figure 6b shows the corresponding true roof albedos corrected using equation 5. It is noteworthy that the measured roof albedo increases with the decrease of the pyranometer height (Figure 6a). Interestingly, but not surprisingly, after correction with equation 5, the true roof albedos tend to be consistent regardless of the inverted pyranometer height (Figure 6b). The absolute and fractional difference between the highest corrected value and the lowest corrected value are approximately 0.022 and 2.6%, respectively. Within the experimental errors, the corrected roof albedos measured at different inverted pyranometer heights are identical. The average true roof albedo of the painted roof is approximately 0.835.

Figure 7a compares the time dependence of albedos of an unpainted flat concrete roof directly measured at different inverted pyranometer heights, and Figure 7b shows the corresponding true roof albedos corrected using equation 5. The similar phenomena were observed for the concrete roof. The absolute and fractional difference between the highest corrected value and the lowest corrected value are approximately 0.012 and 3%, respectively. The average true roof albedo of the unpainted concrete roof is 0. 376. The above observations indicated that the true roof albedo is independent of the selected inverted pyranometer, providing the measurements are carried out during the suitable daily time window. The reflected radiation (thus measured albedo) was found to first increases and then approaches a constant value with the inverted pyranometer height is increased [40]. This observed contradiction might result from the difference between the flat test sectors. The roof area of the model buildings in this study is only 4 m2 but each test sector area in their case was approximately 12 m2 [40]. Large test sample allows the effects of roughness, surface texture and the ground to be better offseted in the albedo measurement [40].

The solar reflectance of the roof painted with the cool white coating measured by a spectrophotometer in the laboratory (0.889) differs from that tested by a pyranometer in the field (0.835) by 0.055, while for the concrete roof, the difference is 0.020. It is widely accepted that solar reflectance varies with the spectral and angular distributions of incident sunlight, which in turn depend on surface orientation, solar position and atmospheric conditions [42]. In the laboratory measurements of solar reflectance by a spectrophotometer (E891 BN), integrating measured spectral reflectance weighted by normal-incidence beam solar spectral irradiance (direct-normal spectral irradiance) yields normal-incidence beam-hemispherical solar reflectance, also referred to as direct-normal solar reflectance [39]. Under clear sky air mass one global horizontal (AM1GH) conditions (a horizontal surface under a clear sky illuminated by one sun at solar zenith), there is only approximately 89% beam radiation for a surface illuminated by unconcentrated sunlight [39]. On the other hand, the near infrared (NIR) fractions of the E891 BN hazy sky beam normal solar irradiance (58.1%) is higher than that of AM1GH solar irradiance (48.7%), yielding large errors in the solar reflectance of a spectrally selective surface [33, 34]. Solar reflectance measured by a spectrophotometer differs from that tested in the field under AM1GH conditions by as much as 0.08 [39].

The measured thermal emittance of the concrete roof is 0.92, which is in good agreement with the literature value. The thermal emittance of painted roof is 0.89, which is slightly larger than the coating's thermal emittance (0.87) measured using the steady-state calorimetric technique [25].

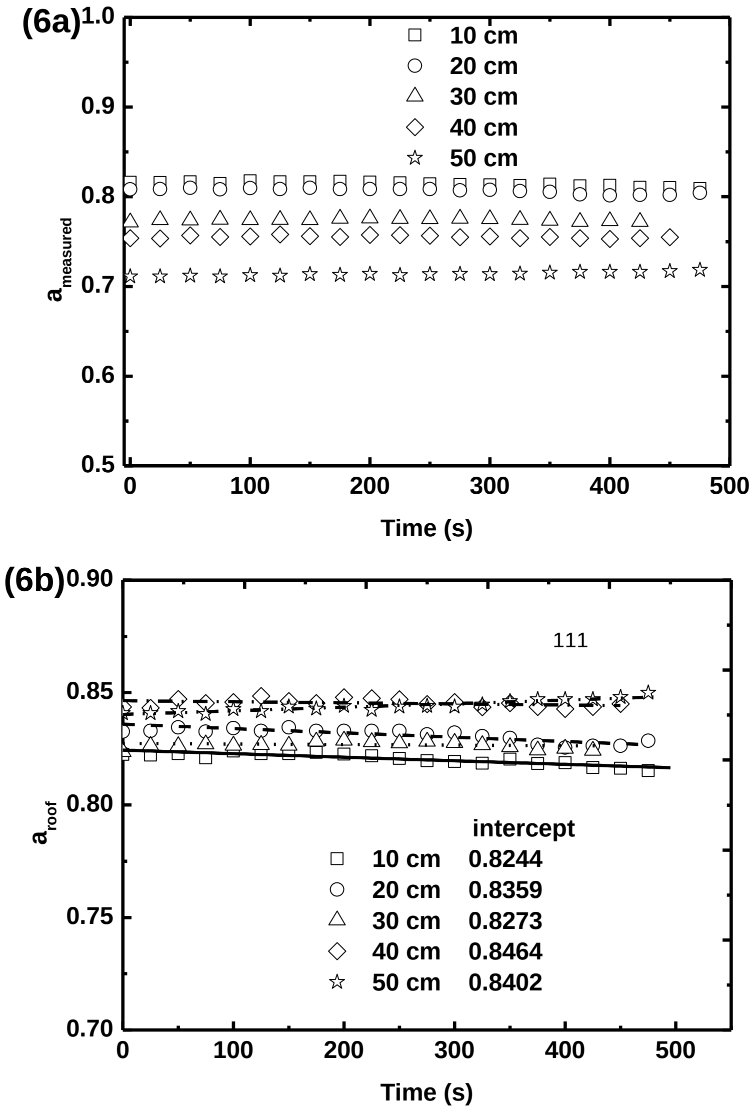

Figure 6. Time dependence of the albedo of a roof painted with a cool white coating for different pyranometer heights indicated. (a) Albedos directly measured on September 21, 2013 and (b) Roof albedos corrected using equation 5. The solid line, dash line, dotted line, dash dotted line and dash dot dotted lines are regressions fit to the corrected data. The roof albedo is 0.835.

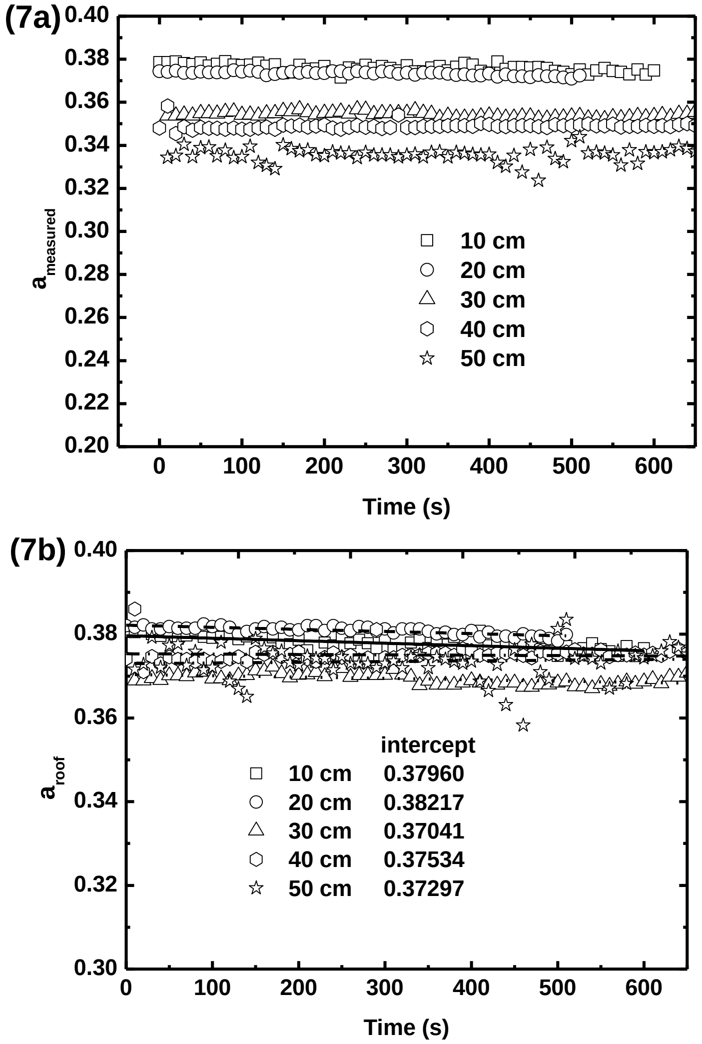

Figure 7. Time dependence of the albedo of an unpainted concrete roof for different pyranometer heights indicated. (a) Albedos directly measured on September 20, 2013 and (b) Roof albedos corrected using equation 5. The solid line, dash line, dotted line, dash dotted line and dash dot dotted lines are regressions fit to the corrected data. The roof albedo is 0.376.

3.2. Estimates of SRI and roof surface temperature

To estimate the cooling effect of the self-developed cool white roof coating, both the solar reflectance of the roofs measured by a spectrophotometer in the laboratory and that measured by two pyranometers in the field were used to calculate the solar reflectance index and roof surface temperature of the painted and unpainted roofs of the model buildings. Clearly, because of the use of the self-developed cool white coating, the SRI increases and the roof surface temperature decreases. The increase of SRI and the reduction of the roof surface temperature are 67.5 and 25.5 °C, respectively, when estimated using the solar reflectance measured by a spectrophotometer in the laboratory; these two values are 62.3 and 23.5 °C, respectively, when calculated using the solar reflectance measured by two pyranometer in the field.

The results also indicate that the solar reflectance measured by a spectrophotometer overestimates the SRI and underestimates the roof surface temperature under the standard conditions specified by ASTM E1980. SRI estimated by the solar reflectance measured by a spectrophotometer differs from that measured by two pyranomters by 2.6 and 7.8 for the concrete roof and painted roof, respectively.

The roof surface temperature calculated by the solar reflectance measured by a spectrophotometer differs from that measured by two pyranomters for the concrete roof and painted roof by 1 and 3 °C, respectively. The solar reflectance measured by a spectrophotometer according to ASTM E891 was found to underestimate the annual peak solar heat gain of a typical low slope roof by as much as 89 W m^{-2}, and underestimate its peak surface temperature by up to 5 K; the solar reflectance measured by pyranometers following the procedures described in reference 33 exaggerated the annual peak solar heat gain of a typical low slope roof by 2 W m^{-2} [42]. Therefore, the roof surface temperature estimated using online SRI calculator is quite reasonable.

3.3. Estimates of energy savings

In addition to the solar reflectance and thermal emittance, the climatological data, roof thermal resistance and coefficient of performance (COE) of the cooling and heating systems also need to be determined to estimate energy savings using DOE cool roof calculator.

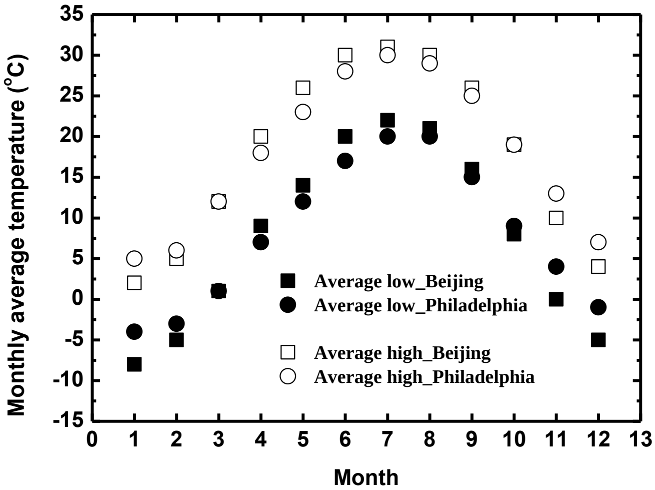

Figure 8. Comparison of monthly average high and low temperatures between Beijing and Philadelphia.

Unfortunately, no information is available for Beijing in the climatological database of the DOE cool roof calculator. As mentioned earlier in this section, one main factor affecting the solar reflectance is solar position [42]. Therefore, to use the meteorological data listed in the calculator, the selected city should have the same latitude as Beijing. The latitude of Beijing and Philadelphia is 39° 54'50"N and 39° 57'12"N, respectively. While Beijing belongs to a continental monsoon climate, Philadelphia features a continental climate. Figure 8 compares the monthly average high and low temperature between Beijing and Philadelphia [43]. Figure 8 clearly indicates that the monthly average high and low temperatures of these two cities are nearly identical, although the atmospheric conditions of them are different. Therefore, it is quite reasonable to use the meteorological data of Philadelphia to approximately estimate the energy and peak demand savings in Beijing by DOE cool roof calculator.

The prototypical model houses used in this paper were not insulated. This is a common feature for old flat concrete houses in Beijing. As the results indicated, the total roof thermal insulation is 0.365 m^2KW^{-1} (corresponding to roof R-value of 2.1 $h \cdot ft^2 \cdot FBtu^{-1}$). The coefficient of performance (COP) of the heating and cooling air conditioner is assumed to be 2.0. Both the roof albedo measured in the laboratory and that tested in the field were used to estimate the savings for an increase in roof albedo from a typical dark roof of 0.1 to a concrete roof and a painted roof, respectively. The difference between these two savings is the savings due to the use of the cool white roof coating.

The results indicate that the annual peak demand and cooling energy savings, heating energy penalty and net energy savings of the model houses estimated by the roof albedo measured in the field are slightly lower than that estimated by the roof albedo measured by a spectrophotometer in the laboratory. This is because the solar reflectance evaluated by a spectrophotometer underestimates the annual peak heat gain and thus the peak surface temperature of a low slope and/or flat roof [42].

In climates, such as in Beijing, where cooling is required mainly in summer and heating is required primarily in winter, the use of the cool white roof coating on a flat concrete roof leads to not only peak demand and cooling energy savings in the summer, but also heating penalty in winter. However, the cooling energy savings is much larger than the heating penalty. The roof albedos measured in the laboratory and in the field yield the annual net energy savings of 6.8 and 6.4 $kWhm^{-2}yr^{-1}$, respectively. In both cases, the peak demand savings are 0.10 $kWm^{-2}yr^{-1}$. Apparently, both measurements yield the similar energy saving results.

Information regarding estimates of the energy savings in Beijing due to the use of cool roof coatings is scarce. Therefore, only little data from other researchers are available to be compared with ours. The estimated annual cooling energy savings of the model houses in this study are 13.7 and 12.7 $kWhm^{-2}yr^{-1}$, respectively, for a 0.493 increase in roof albedo from the concrete roof to the painted roof for the laboratory measurements and a 0.459 increase for the field tests, comparing well with the 12.0 $kWhm^{-2}yr^{-1}$ value in Beijing for a 0.4 increase in roof albedo reported by Synnefa et al [10]. The slightly larger estimated values of this study may be ascribed to the larger increase of albedo and smaller roof thermal resistance. The roof thermal resistance of their simulated prototypic house was 1.19 m^2KW^{-1} and the energy savings were estimated by TRNSYS thermal simulation software. For a typical house with roofing insulation of 1.94 m^2KW^{-1} and the COP of 2.3, increasing roof albedo by 0.3 yielded cooling energy savings of 3.49 $kWhm^{-2}yr^{-1}$ in Beijing. The lower cooling energy saving value is due to the larger roofing insulation, the higher COP and the lower increase of roof albedo.

The simulated energy savings can compare well with the measured values in some cases [22, 44], while large discrepancies may also exist between them in the cases where the user fails to provide the model with the most suitable inputs to describe the monitored building. Furthermore, simulations generally neglect micro- and local-scale climate variations [44]. In addition, the roof albedo may attenuate over time from aging, weathering and soiling [10, 27], although the effects of soiling can be nearly eliminated by regularly washing it with a mild soap solution [24]. Therefore, the simulated results are only representative of the energy savings for the conditions of the simulation and can not be used to replace the measured values. It is necessary to carry out actual measurements. The heating penalty and cooling energy savings will be systematically measured in this winter and the next year.

3.4. City scale energy savings and reduction of emissions

In China, the electricity is mainly supplied by fire engine plants (thermal electricity 83.2%, hydroelectricity 14.7 % and others 2.1%). The CO_2 emissions per kWh electricity generated are 842 g /kWh [45]. The NO_X, SO_2 and carbon dust emissions per kWh electricity generated are 15, 30 and 272 g/kWh, respectively [46].

There are approximately 70 Mm^2 air-conditioned flat concrete roofs in the urban area of Beijing, 70% of which have heights no more than 18 m above ground level and the other 30% are the roofs of high-rise buildings. The owners of apartments in high-rise buildings often prefer non-white roofs of the surrounding low-rise buildings for aesthetic and visual considerations. Thus, the flat concrete roofs of the low-rise buildings are deemed more suitable for roof greening or colored cool coatings. It is quite reasonable to assume that 50% of the roofs of high-rise buildings in Beijing were not thermally insulated. If only these buildings were pained with the developed cool white roof coating, it would yield city scale annual cooling energy savings of 70000000 × 30% × 50% × 13.7 = 143.85 $GWhyr^{-1}$ for the laboratory measurements, and 70000000 × 30% × 50% × 12.7 = 133.35 $GWhyr^{-1}$ for the field tests.

The annual net energy savings would be 70000000 × 30% × 50% × 6.8 = 71.4 $GWhyr^{-1}$ for the laboratory measurements, and 70000000 × 30% × 50% × 6.4 = 67.2 $GWhyr^{-1}$ for the field tests.

The annual peak demand savings for both cases would be 70000000 × 30% × 50% × 0.1 = 1.05 $GWyr^{-1}$.

These annual net energy savings would reduce annual emissions from China's power plants by 60 kton CO_2, 1.1 kton NO_x, 2.1 kton SO_2 and 19.4 kton carbon dust for the laboratory tests and by 56.6 kton CO_2, 1.0 kton NO_x, 2.0 kton SO_2 and 18.3 kton carbon dust for the field tests. Nitrogen oxides (NOx) play an important role in the formation of ozone (O_3) (smog), and carbon dust and SO_2 are components of particulate matter that forms harmful atmospheric haze. Therefore, the above reductions of roof surface temperature and annual emissions due to the use of the cool white coating not only could mitigate the greenhouse effect and urban heat island effect in Beijing, but might improve the air quality by reducing its worldwide known atmospheric haze as well.

4. Conclusions

In this study, the effects of a cool white roof coating on the roof surface temperature, SRI and energy savings of the scale model buildings with uninsulated flat concrete roofs in Beijing were quantitatively estimated using DOE cool roof calculator. The roof albedo measured in the actual outdoor environment is independent of the selected inverted pyranometer heights and time within the daily measuring time window. The use of the cool white coating reduces the roof surface temperature by 25.5 and 23.5 °C and increases SRI by 67.5 and 62.3, respectively, for the laboratory measurements and the field tests. An increase in solar reflectance from 0.396 to 0.889 (laboratory measurements) yields the annual peak demand savings of 0.10 $kWm^{-2}yr^{-1}$, cooling energy savings of 13.7 $kWhm^{-2}yr^{-1}$ and net energy savings of 6.8 $kWhm^{-2}yr^{-1}$. Increasing roof albedo from 0.376 to 0.835 (field tests) generates the annual peak demand savings of 0.10 $kWm^{-2}yr^{-1}$, cooling energy savings of 12.7 $kWhm^{-2}yr^{-1}$ and net energy savings of 6.4 $kWhm^{-2}yr^{-1}$.

Extrapolating the annual net energy savings to the city scale, they would reduce annual emissions from China's power plants by 60 kton CO_2, 1.1 kton NO_x, 2.1 kton SO_2 and 19.4 kton carbon dust for the laboratory tests and by 56.6 kton CO_2, 1.0 kton NO_x, 2.0 kton SO_2 and 18.3 kton carbon dust for the field tests, greatly mitigating the Green House effect and atmospheric haze in Beijing. Compared to the results estimated using the solar reflectance measured by a spectrophotometer, using the roof albedo tested in the field obtains slightly higher roof surface temperature, equivalent annual peak demand reduction, and lower SRI, annual cooling and net energy savings.

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