COMPARATIVE PERFORMANCE TESTING OF METAL ROOFING WHEN BARE and COATED WITH "SKYCOOL"

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AIM

To compare and quantify the cooling performance of "SkyCool" "roof" coatings with that of a bare metal roof for a variety of sky and weather conditions, during both the day and the night.

Summary

The SkyCool surface combines a low solar absorptance and high thermal emittance at "sky-window" wavelengths which leads over a typical 24 hour period of clear skies, to net interior cooling by the SkyCool surface compared to net interior heating by the bare surface with each having no sub-roof insulation. As a guide the net cooling or outflow of heat from the interior under SkyCool over such a 24 hour period is around 350 Watt hours per m^2 of roof compared with the net heating or inflow of heat from the bare surface of around 300 Watt hours per m^2 of roof for the systems set up in this study. The differential impact on cooling demand per day is thus around 650 Watt hours per m^2 of roof for clear skies. Larger inflow and outflow differences might arise when the space under the roof is larger than in these experiments, and in mid-summer when the solar absorptance differences have a larger impact.

PROCEDURES and SET-UP

The insulated metal walls and spaces under each "roof", and the roof areas are identical in size and set up. Only the surface finish of the exposed upper surfaces or "roof" are different.

Relevant data was collected almost continuously over an extended period of time, from March 26 to May 16, 2007. Each coated "roof" area was flat, 916 x 916 mm in area and oriented horizontally. All vertical walls were thermally insulated with R2 batts, but the roofs were not internally insulated so as to better compare their cooling and heating impacts. One upper surface had a coating of SkyCool and one was not coated. The SkyCool surface had been previously aged over a number of years outdoors and its solar reflective properties had changed only marginally, which is an excellent result for a white. Its radiative properties had not degraded at all from the original very high emittance value of 0.95 to 0.96 that we determined some years ago, implying that its constituents had not allowed any uptake into the coating of other materials, significant loss of coating, or crack and void development, despite normal temperature swings, rain and UV irradiation. The ability of these coatings to significantly reduce temperature swings on the high side, as in the following data, enhances their long term durability.

Two types of experiment were conducted

(A) Comparative performance of each unit as constructed
(B) Comparative performance when the central internal temperatures in each space are thermally controlled to be identical.

These distinct studies had to be performed on different days since we only had one example of each system. The controlled temperature experiments were carried out mainly in the first half of the data gathering period, until mid-April and involved controlled heating of the cooler space until its temperatures matched that of the hotter space. The latter was always that under the bare roof. The power supplied to the space under the painted roof is closely linked to its relative solar heat rejection in the day and relative radiative cooling at night, compared to the bare surface. Differences in the two power readings implies a difference in net cooling or heating between the two coatings. The power level readings used for control do not give absolute cooling powers. These are larger and must be found by adding the lower cooling power of the bare surface, which has to be estimated from its properties. This is typically at night at least half that of the coated surface, since the bare roof also cools to temperatures well below ambient, but at a slower rate. At night, especially under still conditions, once roof temperature drops below ambient the recorded power gives a very close approximation to the relative radiative cooling powers to space, which is at a very much lower temperature than most of the atmosphere. The latter radiates back to the coated or bare surface once it is below ambient and it is this radiation from the atmosphere at all black body wavelengths, that ultimately limits the temperature drop at night. The limited part of the black body spectrum which allows sub-ambient cooling is outlined later. As well it mainly involves higher "view" angles of the sky since at lower angles the atmosphere is thicker and "space" is only weakly viewed. At a few hours before dawn this and other factors cause the differentials to drop and roof temperatures to converge as they reach their coldest. In particular direct heat gain from the environment starts to match radiative loss as the rate of temperature fall drops, and in some cases some water condensation may also have removed the relative impacts of radiative loss, though this effect seems to be secondary.

In the daytime these power readings depend on relative lowering of heat gain from the coated roof compared with that of the bare roof. It is dominated by the relative amount of solar energy absorbed by each roof. They are also affected by the relative heat transfer coefficients on both sides of the roof, which govern the net inflow of heat into the space under the roof, and out into the atmosphere from respective surfaces. Exterior wind will raise the outer flows, as will elevation of external radiative losses compared with those inside, due to the coating. The quantitative analysis of these factors is more complex than at night because the interior and roof temperatures are well above ambient so convective transfers are now significant, and because the coated and bare roof temperatures differ much more than at night. However there are still worthwhile benefits from the better radiative performance of the SkyCool paint, in addition to those arising from its much lower solar absorptance. However it is solar absorptance that dominates in the daytime. In these more complex heat flow circumstances in the day, with a constant internal temperature means even just relative roof temperature data is still very useful as a simple measure of overall relative thermal performance. For common internal temperatures relative internal heat flow is almost directly linked to roof temperature. This follows because internal surfaces have nearly identical heat transfer coefficients apart from small corrections due to one being hotter. Thus we can estimate absolute heat flows by combining both temperature and relative input power data and this is done in the results section.

Materials and the interplay between optical and thermal properties

Surface optical properties that can be measured in our laboratory and that influence the performance are hemispherical thermal emittance and solar reflectance. These values correlate well with the main features of thermal behaviour. However once the surface temperatures drop below ambient, which they do soon after sunset on most clear nights, radiative loss is governed by radiation at sky-window wavelengths (7.9 µm to 13 µm), not the whole black body spectral range (3 µm to 28 µm). The limited range is thus more important for roof cooling in the night than the emittance averaged over the whole black body thermal range. Most of the black body range ceases to contribute to cooling if ambient is above the roof temperature. Many common high emittance coatings, including that in this study, have high absorptance and hence high emittance across most of the black body wavelength range, including the sky window range, so they continue to function well only until their temperature drops to around 4° to 8° C below ambient. At this point incoming radiation from the "non-window" parts of the atmosphere and the local environment (which are absorbed strongly) , balance the losses through the sky window and temperature ceases to fall. The biggest differences are apparent earlier in the night when the higher emittance surfaces cool much more quickly and thus spend more time at lower temperatures. To attain even lower temperatures requires high reflectance, at "non sky-window" radiating wavelengths combined with high absorptance across the sky-window. SkyCool does not have such spectral selectivity. The benefits of such special spectral properties would only become apparent if it is desired to work at temperatures more than 7°C below ambient with special structures designed to further reduce incoming heat which is a bigger problem once T drops this low. <u>That is, for most standard or normal roofs it will be difficult to do much better than the SkyCool system,</u> though higher levels of radiative cooling to the sky at night are possible with roof modifications both for SkyCool and for those narrower band radiators which only emit strongly across the sky window. <u>None of the latter are yet commercial</u>.

Note that the orientation of a surface, and even the intrinsic profile of a metal roof, can <u>have significant impact on its cooling ability</u>. In the day tilting towards the sun enhances solar absorptance, tilting away from the sun or partial shading reduces it and may even allow radiative cooling to dominate to achieve net cooling in the daytime. At night tilting towards the horizon reduces sky cooling. As noted above the transmittance at the sky window falls as the azimuth angle falls (i.e. as tilt increases). The atmosphere becomes more absorbing and more radiating at sky-window wavelengths for radiation increasingly closer to the horizon. This is one of the main limiting factors on night cooling. If lower angle views of the sky are blocked due to adjacent structures or nearby buildings, the emittance of these structures becomes important and may increase or decrease cooling rates. <u>In our set up adjacent brick wall structures and buildings were impacting to some extent</u>.

A laboratory comparison was made between fresh and old outdoor aged SkyCool coatings since the test roof had been aged. Thermal emittance had not altered (within experimental accuracy of 1%) from its original value some years ago of 0.95±0.01. The solar reflectance however had degraded slightly by about 2%, which is an excellent result from a long term performance perspective.

Data recorded and plotted

(A) Time, mostly at one minute intervals.
(B) Internal temperature in the centre of the space, roof temperature near the centre and ambient temperature, all using thermocouples.
(C) Solar insolation
(D) Power to the lamps inside each painted box, as required to match the temperature inside the unpainted box.

The experiment was controlled, and all data recorded via a LabView program which we wrote and set up for this project. It ran continuously, except when we stopped to download data, alter the experimental protocol, or make periodic checks on accuracy. Periodic difficulties were encountered with the power level recording sensor, because of the fluctuating nature of the switching control which regulated the power. Control to equalise relative temperature was maintained, even when the sensor outputs and hence power data was fluctuating excessively. That is it was a power sensor problem, but temperature was held correctly, as this was linked directly to temperature readings and the switching control worked fine. Despite this sensor problem a sufficient number of days of steady recordings of power gave us enough good data to perform the desired quantitative analysis. The relative temperatures on the lids in the day and night, with equal controlled interior temperatures, still enabled us to do additional analyses not possible when data was recorded when each box was operated independently and to check our analyses on days when we had useful power readings.

Results and analysis

A set of plots are located in the appendix. They cover the various types of data that were acquired. The plots are approximately in sequence of their date of acquisition, with the plots of early data involving one to five consecutive days and controlled interiors under the coated roofs. Later plots are for no internal temperature control and each incorporates up to a week of data. The full set of numerical data is available if desired on Excel spreadsheets, including all relevant plots.

Comments follow on each plot then some relevant quantitative analysis is done to yield absolute parameters and cooling and heating powers, in addition to relative performance for each system. Cooling powers are presented as measured for each box, and must be divided by area (A =0.839 m^2) to convert to units of Wm^{-2}. Controlled means common interior temperatures to that of hottest interior, which is always under the bare roof if there is no control.

Set A. 1 day March 28, 2007 - Controlled
Plot A1 Cooling power
Plot A2 Lid and ambient temperatures
Plot A3 Interior and ambient temperatures

SkyCool has a cooling power of about 35 Watts above that of the bare roof most of the night except for the hours before sunrise, and its heat gain in the day averages around 60 to 70 Watts less. This is good given its low angle "view" of surrounding structures.

Set B. 3 days to March 30, 2007 - Controlled
Plot B1 Cooling power in Watts
Plot B2 Lid and ambient temperatures
Plot B3 Interior and ambient temperatures

SkyCool cooling power is again about 35 Watts above that of bare roof most of the night except close to sunrise, and heat gain in the day around 60 to 70 Watts less, but peaks show relative heat input drops by as much as a 100 Watts. From the evening data on powers we can estimate heat transfer coefficients and hence establish basic models for cooling which can be checked. Results using this analysis appear below. Plot B2 shows for the lids a large residual difference because heat transfer from the roof to the common interior is much lower than the solar heat gains and exterior heat loss. Without interior control the SkyCool lid would thus be much cooler than in these plots as verified in later data and analysis with no control.

Set C. 2 days to April 2, 2007 - Controlled
Plot C1 Cooling power in Watts
Plot C2 Lid and ambient temperatures
Plot C3 Interior and ambient temperatures

SkyCool cooling power is about 25 Watts above that of the bare roof most of the night, except close to sunrise. The difference approaches zero as it seems to be partly cloudy as also seen in the next two days. Reduction of heat gain due to the coating in day one is around 60 to 70 Watts with peaks at 80 Watts . These values are less than in plot B1 due to some cloud. The bare lid is much hotter in the daytime even though it is partly cloudy. The bare is slightly colder at night relative to the coated lid in this experimental set up due to some direct heat transfer from the heating elements to the lids in the two controlled interiors. It is never cooler when interior control is absent.

Set D. 5 days to April 5, 2007 - Controlled
Plot D1 Roof and ambient temperatures
Plot D2 Interior (common) and ambient temperatures

Overall features as in A, B, C above. All lid night temperatures well below ambient with largest drops on clear nights. While both are cooling SkyCool remains about 2 degrees below the bare lid temperature until early morning, when they converge. The coated lid would be further below but heating input to its interior also directly raises its lid temperature as noted in set C comments.

On clear nights the controlled interiors in plot D2 spend much of the night at around 5 to 7 ° C below local ambient as a result of radiative cooling. This was regarded as a little too low on theoretical grounds. It was then found that actual ambient temperatures from the weather bureau data and from placing our sensor higher above the building roof was 1° to 1.5 °C higher than we had been recording as local ambient, due to residual heat from roof keeping our original sensor position above ambient. It was thus relocated for subsequent recordings.

When accounting for actual estimated cooling rates of the bare roof, then adding relative cooling powers at night as in B and C above for coated roofs, it is apparent that the SkyCool coating can achieve a little in excess of 50 Watts net or absolute cooling on clear night at temperatures around 4 to 6°C below ambient. We quantify this more precisely later. This is about as expected for a good radiator which is close to a black body spectrally. This equates to 60 Wm^{-2} of cooling power in early evening, though net cooling power density drops below this an hour or two before sunrise, once temperature drops to near its lowest for the night.

<u>Set E, F, G – No interior Control</u>
<u>E - 4 days to April 12, 2007</u>
<u>F - 4 days to April 30, 2007</u>
<u>G - 5 days to May 4 , 2007</u>

Plot E1, F1, G1 Roof and ambient temperatures
Plot E2, F2, G2 Interior and ambient temperatures

These sets on clear days display very similar temperature–time profiles over the whole month. In the daytime the lids on bare roofs reach 55°C to 60° C (or 30 to 36° C above ambient) while those on SkyCool reach 30° C to 31° C (or 8 to 10° C above ambient). After sunset in clear sky conditions, the lids cool rapidly below ambient at first in about half an hour, by 3 to 4° C for the coated roof and 2 to 3° C on bare. After that period the gap to ambient opens up further over the night reaching up to 8 ° C on the coldest and clearest nights in early May. Generally the difference is about 7°C in April for the coated roof.

In these experiments with no interior temperature control, the coated roof clearly has greater radiative cooling power than the bare, as expected from the earlier power data. This means it acquires 1 to 2° C lower temperature, whereas in the control experiments they actually had slightly higher temperature values for reasons explained above. This is until of order 2 hours before dawn when all lid temperatures converge as heat inflows match outflows and T minimises. Once direct exposure to sunlight occurs there is a rapid rise above ambient in the bare, and a much slower one for coated roofs. On some nights the coated roof temperature always remains below that of the bare roof. On others they converge. It is with the clearer conditions that they stay apart. Thus the impact of relative sky cooling powers is often not eliminated over a whole clear night in terms of final temperatures as incoming heat is lower.

Interior temperatures at night are only 2 to 3° C above roof temperatures and this may in part be due to residual heat from building below. There is a rapid following of lid values due to the small volume of air in our "spaces". In an actual building roof a much larger thermal mass of air and interior fittings with stored heat from the day is expected to make this difference larger.

Set H, I – No interior Control
H 9 days to May 8, 2007
I 9 days to May 16, 2007

Plot H1, I1 Roof and ambient temperatures
Plot H2, I2 Interior and ambient temperatures

These data follow the patterns of the previous data sets (E, F, G) . The only major addition is the clear comparison they allow to the impact of a few cloudy days against clear days. On cloudy days there is convergence of all temperatures.

Overall results and parameters

From the results with common internal temperatures the associated control powers are a useful guide to differences in cooling and heating rates. Actual performance without control involves lower internal temperatures under the coated roof and hence different cooling rates. The bare case is unchanged but we need to estimate its rates to get absolute values. However this control data, and its relative rates, are still of use in two ways. First even though a relative measurement, it still gives a guide to actual cooling and heating rates. Actual cooling rates will be higher, and heating rates will be lower for the coated roofs. Secondly it simplifies accurate analysis of heat flow coefficients on both sides of the roof surfaces. Once derived these coefficients can be used in various ways to model cooling and heating rates, and surface temperatures under normal operation, that is without control. These predictions can then be checked against actual data when control is removed, which was done here. It turns out that any corrections to coefficients for internal temperature changes are small and can be estimated. All calculations must also be consistent with the laboratory measured solar optical and emittance data. In particular in the daytime differences in internal heat gain must link to differences in solar absorption, and differences in cooling rates at night when roofs are below ambient, must link to differences in rates of radiative loss to space and hence to thermal emittance at a particular range of wavelengths.

Data from Controlled interiors

Daytime

The relative power input ΔQ to raise the temperature in the space under the coated roof to that of the space under the bare roof, directly links to the differences in roof temperatures in the daytime as follows

$$\Delta Q = h_{int}(T_{r,coat} - T_{r,bare})$$

with h_{int} the surface heat transfer coefficient from the underside of the roof to the space below and $T_{r.coat}$, $T_{r.bare}$ the respective measured roof temperatures. h_{int} will be similar for both boxes as undersides are not coated. It has a slight T dependence over the range of this study.

For the coated surface these controlled internal temperatures were seen to be close to the roof values, within about 2°C to 3 °C. This means most of the observed differential from electric power data in heating rate to raise them to these levels, is due directly to the large amount of inwards transfer from the much hotter bare roof. This is in turn due to its much larger solar absorption $A_{sol, bare}$, which is of order $4xA_{Sky Cool}$ from a full analysis and from optical data.

The observed daytime differential values in plots B, C of around 75 to 85 Wm^{-2} are thus only about 10 Wm^{-2} below the actual influx from the hotter bare surface into its interior.

From this type of analysis assuming a common h_{int} and knowledge of $A_{sol.coat}$, $A_{sol, bare}$ and measurement of solar fluxes we can also estimate from detailed heat balance equations, h_{out} , the coefficient in the daytime for heat transfer to the ambient from the outer surface. This will rise as air flow velocity v increases. The heat balance at steady state under solar illumination of Φ_{SUN} Watts m^{-2} is

$$A_{SOL}\Phi_{SUN} = h_{out}(T_s, v, e)[T_s - T_{am}] + h_{in}[T_s - T_{in}]$$

with T_S the surface temperature, T_{am} the ambient temperature and T_{in} the interior temperature. The surface temperature, wind speed (v) and thermal emittance (e) dependence of h_{out} is noted explicitly for reference, as it will be important in practice. This equation can be used for the actual area or per unit area. A quite different equation applies at night with no sun, and $T_s < T_{am}$ (see below).

We will present data for still conditions. There will be larger differences between the bare and coated h_{out} but the two factors; the hotter bare surface; and the higher thermal emittance in the coated, cancel to some extent. For simplicity we make both h_{out} equal and find reasonable consistency in doing so with overall data and with prior estimates of such coefficients. Good indicative values for still conditions in this set up are $h_{int} = 3\pm0.5$ $Wm^{-2}°C^{-1}$ and $h_{out} = 6.5 \pm 0.5$ $Wm^{-2}°C^{-1}$. The outer one can exceed 10 $Wm^{-2}°C^{-1}$ for moderate wind speeds. Convection transfer inwards is limited in this set up, hence the low internal value, and is expected to increase for larger interior spaces. It will also be higher with a larger differential as when there is no control, but not by more than 10%. In general heat transfer coefficients are smaller for horizontal than tilted or vertical surfaces. If insulation was used under the roof h_{int} decreases and h_{out} increases at a given solar flux.

As a check we can use these values to estimate roof temperatures and heat flows when there is no control. For instance on April 30 data for coated roofs absorbed solar flux is 80 Wm^{-2}, ambient is 23°C and the interior is 28°C. Applying the heat balance equation one finds T_s = 32°C as found experimentally, and inflow of heat is just 15 Wm^{-2}. The inflow at this time near noon for the bare roof using same h coefficient is 42 Wm^{-2} though this rate should be higher earlier when it is heating up, while near noon it is close to stagnation. On the basis of solar absorptance data it appears also that h_{in} is underestimated for the bare roof as expected, because of its much higher temperature. Using solar absorptance and solar flux data instead, inflow is found to be around 50 Wm^{-2} since h_{in} for this surface is then close to 4 $Wm^{-2}°C^{-1}$. Near stagnation most of the heat is going out from such a hot surface, around 310 Wm^{-2}, for a solar flux of 800 Wm^{-2}.

<u>Night time</u> differentials in surface cooling powers link closely to differential cooling rates measured in our experiments, with common interior temperatures via control. The most important feature is that the <u>roof temperature is below ambient</u> so heat flows in from the environment, but net cooling still occurs. In this analysis we take the roof surface to always be below ambient. Detailed analysis is more complex than in the day because the atmosphere and sky contribute to heat flows in three ways.

(i) Cooling by radiation to space, mainly over the 8 µm to 13 µm band
(ii) Absorption of thermal radiation from the hotter atmosphere at non-sky window wavelengths, and at lower incoming angles at all black body wavelengths with some radiation also from surrounding structures.
(iii) Convective and other non-radiative heat transfer from the surrounds to the roof including from the interior (which is slightly warmer than the roof). The interior is below ambient in this set up but in an actual building may not be.

As a result both internal and external surface transfer rates change from the day values both in direction and magnitude and the prior heat balance equations are not suitable. A further complication is that the observed differentials change significantly as dawn approaches when the incoming heat flows (ii) and (iii) start to match the outgoing heat (i). The differentials are steady however for much of the night, even though both net cooling rates are slowing as the night proceeds.

As a first approximation we could treat the cooling from the bare roof as low enough to neglect. Then the differential cooling rate around 25 to 35 Wm^{-2} is a base estimate. However the bare surface also cools to well below ambient, just more slowly so we need to estimate its rate also then add it on, to get actual net cooling from the coated roofs .

The approach that was adopted was to take previous theoretical analysis of net radiative cooling rates as a function of the temperature drop of the surface below ambient for a horizontal black body. Our coated surface will have approximately 0.95 of this rate and the bare surface around half using previously estimated emittance values. This analysis took account of all angles of incoming and outgoing radiation and hence the variable transmittance at the sky window with azimuth direction. We then add estimates of convective heat gain for net cooling rates to get total flow, and check for consistency with our data.

The net radiative cooling [(i) and (ii) together] is estimated at 60 to 65 Wm^{-2} for these coatings at 7°C below ambient, as is common in the data. Convective or other incoming heat from both sides is estimated at 8 to 11 Wm^{-2}, giving a total net cooling power of 49 to 56 Wm^{-2} or around 45 W for the actual coated roof surfaces, when their area is factored in. The corresponding numbers for the bare surface are around 30 Wm^{-2} and 9 Wm^{-2} for a net rate of 21 Wm^{-2} or 17.6 W for the box areas in the experiments. The differential is thus 27 to 28 Watts. The typical observations in B, C plots have this differential over much of the night within the range 25 to 35 Watts in agreement with these estimates. There is however a sharp drop in the differential for 1.0 to 1.5 hours before dawn. *Thus we conclude that over much of a clear night (9 to 10 hours) the coated roof will have a net cooling power or heat outflow around 50* Wm^{-} *and the bare roof a net outflow of around 20* Wm^{-2}.

This outflow in a real building will be higher in both cases while the roof will not drop in temperature as much below ambient due to the larger thermal mass of air below and the likelihood the space will contain many objects sitting at higher temperatures than the spaces in this experiment. In addition any non-radiative inflow from the outside air will be a lot less due to the reduced drop below ambient. Analysis indicates net cooling powers with SkyCool for an actual coated roof might be as high as 60 to 70 Wm^{-2} for up to 10 hours per night on clear nights.