Cool roofing in cold climates:
A contradiction or a potential for energy savings?

Mark Murphy, M.Eng. [1]
Steinar Grynning, M.Eng. [1, 2]
Bjørn Petter Jelle, Professor [1, 2]
Arild Gustavsen, Professor [2]
Matthias Haase, Associate Professor [1, 2]

[1] SINTEF Building and Infrastructure, Norway
[2] NTNU - Norwegian University of Science and Technology, Norway

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SUMMARY:
In modern buildings with constantly growing demands for levels of thermal insulation and air-tightness, the demand for cooling is rising. The need for cooling is especially common for office buildings, with high internal energy loads that generate surplus heat. A potential method to reduce the cooling demand is to apply a light coloured surface to the building's exterior walls and roof. Solar radiation is then reflected and the temperature of the surface remains cool, in contrast to a dark surface that will absorb the majority of the incoming solar radiation and in the process become warm.

This work investigates the energy savings potential of cool roofing in cold climates through numerical simulations of an office building following Norwegian TEK10 building codes. Additional simulations are also performed to study the impact on indoor climate and to investigate the thermal performance of light coloured roofs. As the internal heat gains become larger and the importance of cooling increases, a reduction of the roof's solar absorptivity will provide a marginal energy savings within a cold climate.

1. Introduction

The use of light colours has been a well known technique to lower indoor temperatures in warmer climates throughout history. One only has to glance to the Mediterranean countries to realize this; there the dominant building tradition makes use of white houses and buildings. In such climates the use of light coloured roofing systems, as well as light coloured facades, is more likely to lower the cooling demand. This reduction in cooling demand decreases simultaneously the strains on electric grids by levelling out peak demands, while building materials experience longer expected lifetimes as a result of decreased thermal stresses. Additionally as the air surrounding the building is heated up to lesser extent, it is possible that the urban heat island effect is accordingly decreased.

These advantages may or may not be transferable to a more Nordic climate, where the heating demand is usually dominant. Are the cooling demands important enough to justify painting the roof white in a Nordic climate? How does the solar absorptivity/reflectance of the roof affect the heating and cooling demands of the building during the course of a year? Does the decrease in cooling demands offset the increase in heating demands? How is the indoor thermal climate affected by the solar absorptivity/reflectance of the roof? These questions and more will be answered within this work.

1.1. Building Materials

Different materials have different abilities to emit, absorb, and reflect light of various wavelengths. As shown in the figure below, the solar reflectance associated with common building materials varies greatly. Red-brown roofing tiles reflect between 10 and 35% of the incoming solar radiation (absorbing 65 to 90%). White paint reflects approximately 70% while asphalt/tar reflects only 10% (McMullan, 2007).

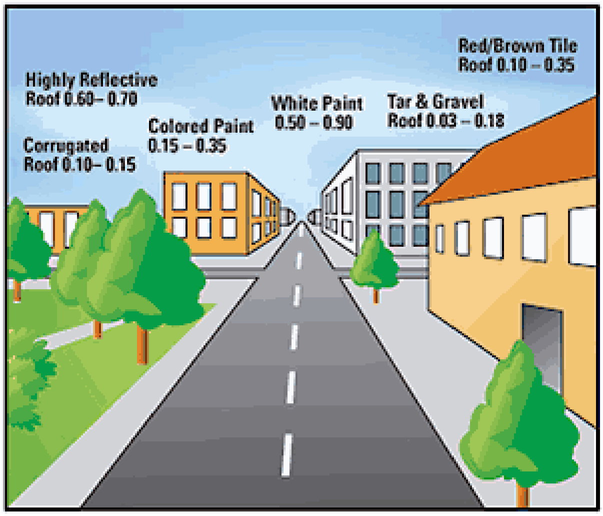

FIG 1. Illustration of possible reflection factors for various building components (Coolroofs, 2009)

So called *cool roofs* have surfaces with high reflectance to solar radiation and high emittance in the infrared spectrum (Levinson et al. 2005). High solar reflectance increases the amount of sunlight, and thus heat energy, which is reflected away from the roof. In addition, the high emittance allows the already absorbed heat within the roof to escape to the surrounding environment. Combined, this will in principle give a lowered surface temperature on the roof.

The surface temperature on a black roof with a low reflectance factor can be as much as 50 °C higher than the ambient temperature in extreme conditions (Synnefa et al. 2007). If one applies a high reflectance surface (usually white paint) the temperature difference can be reduced to 10 °C (Synnefa et al. 2007) above the ambient temperature.

As the cooling demand is proportional to the temperature difference over the construction, the lowered surface temperature on the roof will provide energy savings in the form of reduced cooling costs. However, the potential gains in reduced cooling demands must be weighted against the increase in heating demands for the days when the outdoor temperature is lower than the desired indoor air temperature.

2. Method – Simulation Setup

2.1 Thermal Performance – Indoor Climate

The thermal performance of a compact roof following the minimum requirements from TEK10 (2010) was evaluated on a component level with the help of TRNSYS, WUFI, and Comsol Multiphysics. When following standard guidelines according to SINTEF Building and Infrastructure – Building research Design Sheets (2003), a compact roof consisting of 20 cm concrete and 16 cm XPS insulation with a heat conductivity of 0.038 W/m^{2}K gives a roof construction with the minimum U-value of 0.18 W/m^{2}K.

2.2 Energy Savings Potential

To investigate the energy savings potential of cool roofs, the top floor of an office building was simulated with TRNSYS using the minimum component requirements according to TEK10 building codes. The windows, roof, and walls had U-values 1.2, 0.18, and 0.22 W/m^{2}K respectively. The internal heat gains were simulated first with 30 W/m^2 and then with 40 W/m^2. More than adequate heating and cooling was installed in order to maintain the indoor temperature between 19 and 25 degrees all year round. The window to wall ratio was 20%, the total floor area was 1200 m^2, and the floor to ceiling height was 2.5 meters. For comparison, the building was also simulated with only 5 cm insulation in the roof while being located in the hot climate of Los Angeles.

3. Results

3.1 Thermal Performance – Indoor Climate

Using Comsol Multiphysics, the compact roof was simulated for 24 hours with solar radiation data from two different dates, the 15th March and the 15th July. The total radiation on a horizontal surface in Trondheim was imported from TRNSYS.

Figure 2 below represents the steady state initial conditions that were used to initialize the 15th March simulation.

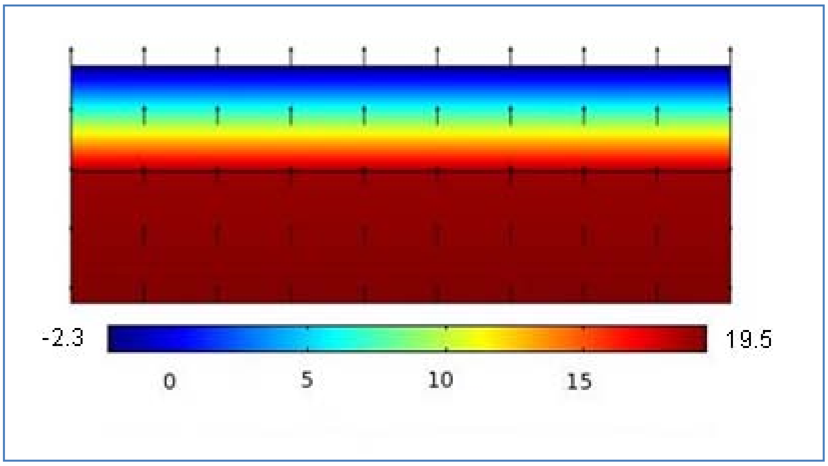

FIG 2. Steady state temperature distribution through the compact roof with -2.5°C outdoors and 20°C indoors. The heat flux is represented by arrows.

The results of the transient simulations are shown in Figure 3, where the heat flux through the external surface is plotted against varying solar absorptivities. Positive heat fluxes represent energy leaving the building, while negative heat fluxes represent solar heat gains entering the roof in excess of transmission losses. After 5 pm, the heat losses to the environment increase above steady state conditions. This occurs since the outer surface has been heated during the day and the flux of solar radiation inward is no longer present or large enough to counter the increased transmission losses.

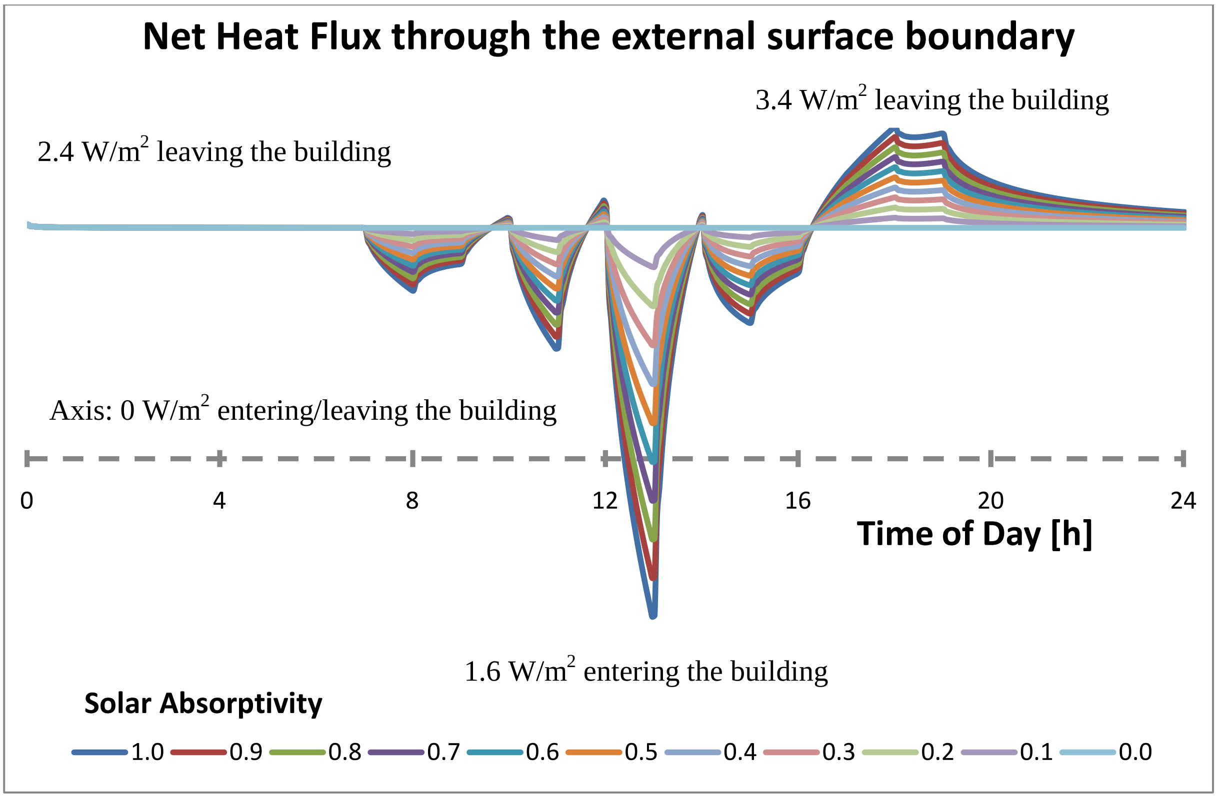

FIG 3. Average heat flux through external surface boundary for 15th March transient simulation through varying solar absorptivities. Constant outdoor and indoor air temperatures. Solar data with weather fluxuations extracted from TRNSYS.

When the temperature within the building is tempered to 20 °C and the convective heat transfer coefficient between the room and the ceiling is 10 W/m^{2}K, the temperature of the indoor surface remains relatively constant. It is first during the summer, as shown in the 15th of July simulation represented by Figure 4, when the indoor surface temperature slightly shifts away from its ideal 20 °C. This shows that it is the heating and cooling system affecting the indoor climate far more than the solar absorptivity of the outer roofing surface. This more or less constant indoor surface temperature was reproduced within the WUFI simulations.

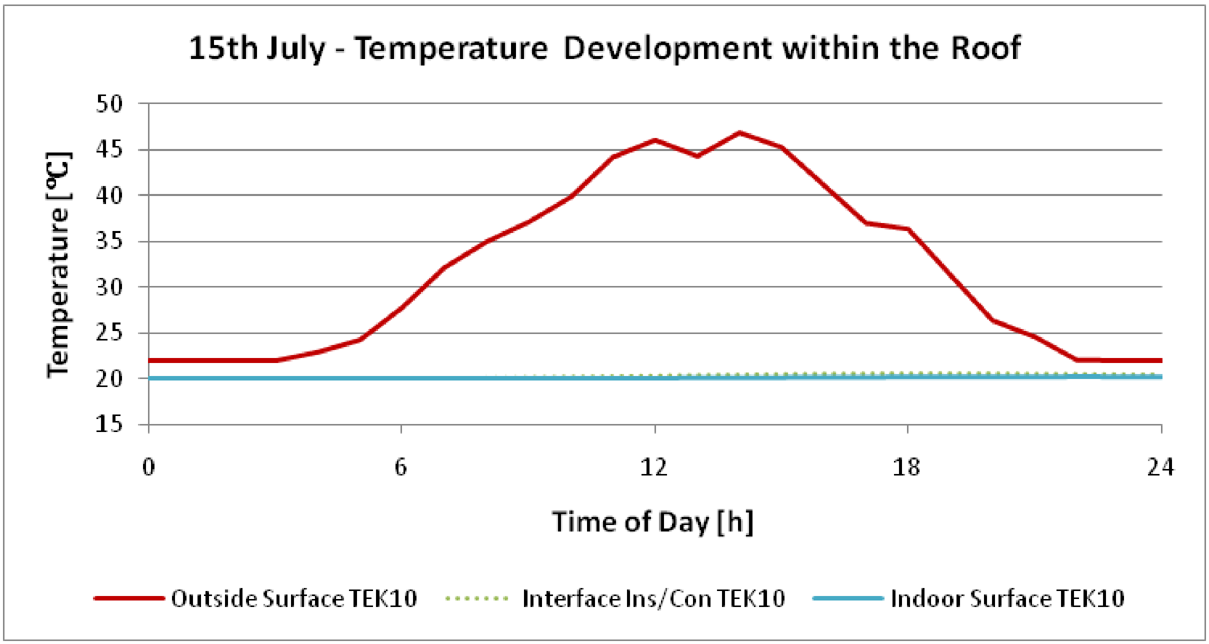

FIG 4. Temperature development of the indoor surface, interface between the concrete and insulation, and outdoor surface during 24 hours using solar data extracted from TRNSYS for the 15th July in Trondheim

Following the indoor and outdoor surface temperatures through a range of solar absorptivities using TRNSYS gives Figures 5 and 6. Here it can be seen that the indoor surface temperature is more noticeably shifted upwards during the summer months than in Figure 4. The indoor surface temperature shifts upward by approximately 0.5°C at most, while the outdoor surface temperature can be as high as 20°C warmer.

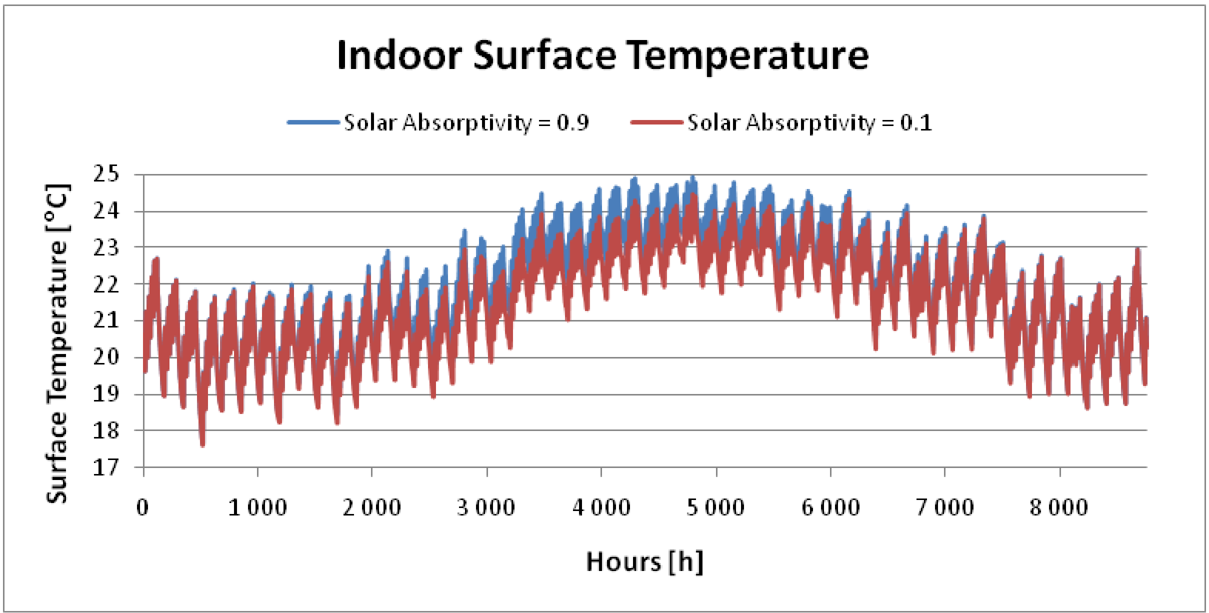

FIG 5. Indoor surface temperature with solar absorptivity = 0.9 and 0.1 (TRNSYS)

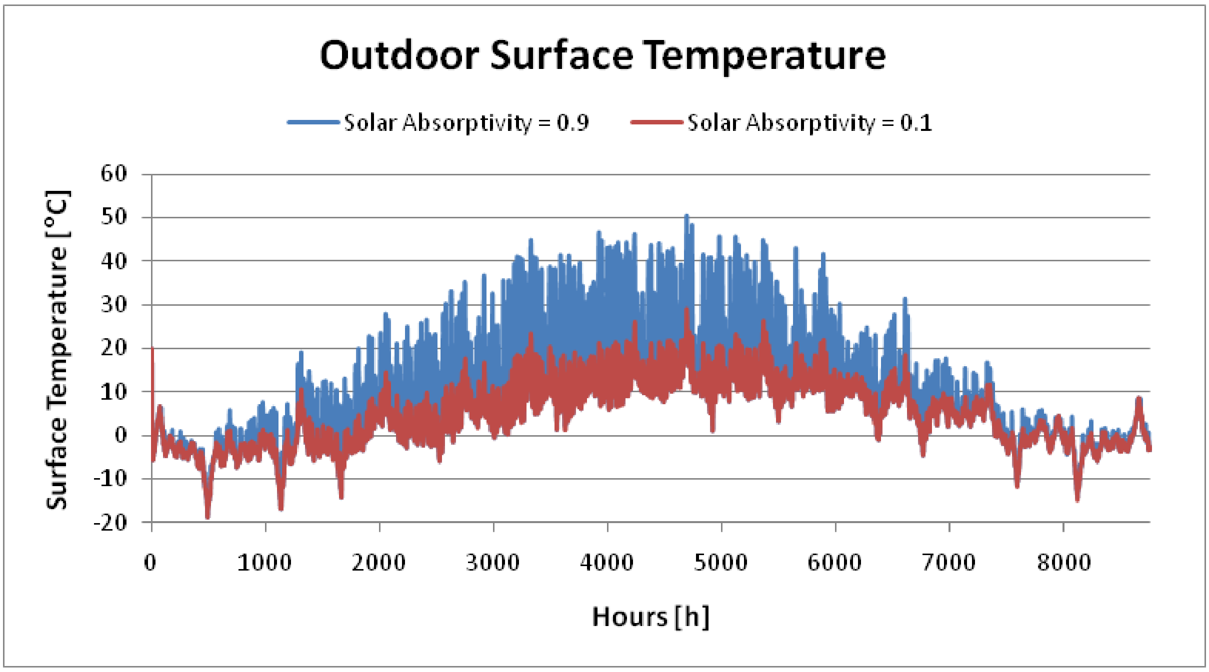

FIG 6. Outdoor surface temperature with solar absorptivity = 0.9 and 0.1 (TRNSYS)

3.2 Energy Savings Potential

When simulating the top floor of an office building over an entire year, varying results are obtained depending upon the internal heat gains and the climate. In the Trondheim office building with 30 W/m^2 internal heat gains, a minimum in the total energy consumption is obtained with a solar absorptivity of 90%. As the internal heat gains are shifted from 30 to 40 W/m^2, the relative importance of the cooling demands increases. As a result, a general trend is obtained that shows, in Table 1, that the total energy consumption decreases as the solar absorptivity decreases, but only marginally.

The specific energy savings potential [kWh/m^2] is found by dividing the change in the total energy demand by the total floor space of 1200 m^2. Relative a black surface with a solar absorptivity of 0.9, the specific energy savings potential is approximately 0.6 kWh/m^2 for the Trondheim office with 40 W/m^2 internal heat gains. In comparison, the building simulated in Los Angeles with a roof containing only 5 cm insulation has a specific energy savings potential of 8.6 kWh/m^2 relative the black surface.

TABLE 1. Annual Space Heating and Cooling Demands [kWh]

	30 W/m^2 Trondheim			40 W/m^2 Trondheim			40 W/m^2 Los Angeles		
Solar Abs.	Heating	Cooling	Total	Heating	Cooling	Total	Heating	Cooling	Total
0.9	14315	741	15056	8358	6175	14534	805	20670	21475
0.6	14685	409	15095	8560	5686	14245	1166	15405	16571
0.3	15100	182	15282	8788	5174	13962	1641	11514	13155
0.1	15399	96	15495	8957	4819	13776	2082	9060	11143

4. Discussion and Conclusions

For a thermally well insulated roof, changing the solar absorptivity of the roof surface has little to no effect on the indoor surface temperature. It is the capacity of the heating and cooling system that determines the quality of the indoor climate since the operative temperature is unaffected by the solar absorptivity of the thermally well insulated roof. The outdoor surface temperature does, however, decrease significantly if the solar absorptivity is decreased. This decreases the cooling demands, but at the same time increases the heating demands. The balance between the two heating and cooling modes will depend upon the structure being evaluated and its internal heat gains. A small house in a cold climate with practically no cooling demand will find a dark roof more profitable as the solar heating gains during the spring and autumn will decrease the annual heating demands. An office with a high internal heat gain might on the other hand find a lighter coloured roof more profitable, but the differences are small.

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