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Cool roof technology in London: An experimental and modelling study

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ABSTRACT

One of the primary reasons for the application of cool materials is their energy and associated environmental impact on the built environment. Cool materials are usually applied on the roof of buildings to reduce cooling energy demand. The relative benefits of this reduction depend on the construction of the building, external weather conditions and use of the building. This paper examines the impact from the application of a reflective paint on a flat roof in a naturally ventilated office building in the area of London, UK where the climate is moderate with high heating demand by buildings. The environmental conditions (internal/external air and surface temperatures) of the building were monitored before and after the application of the cool roof during the summer. It was found that internal temperatures were reduced after the application of the cool roof. The building was modelled using TRNSYS and the model was calibrated successfully using the measurements. A parametric analysis was carried out by varying the reflectivity and insulation of the roof and ventilation rate; the heating and cooling demand for a year was calculated using the Summer Design Year for London as the weather file. It was found that cooling demand is significantly reduced, heating demand is increased and the total energy savings vary between 1 and 8.5% relative to an albedo of 0.1 for the same conditions. In free floating (naturally ventilated) buildings summer comfort is improved but there is a penalty of increased heating energy during the winter. Thermal comfort can be improved by an average of 2.5 °C (operative temperature difference for a change of 0.5 in albedo) but heating demand could be increased by 10% for a ventilation rate of 2 air changes per hour. The results indicate that in the case of temperate climates the type, operation and thermal characteristics of the building should be considered carefully to determine potential benefits of the application of cool roof technology. For the examined case-study, it was found that a roof reflectivity of 0.6–0.7 is the optimum value to achieve energy savings in a cooled office, improve summer internal thermal conditions in a non-cooled office (albeit with some heating energy penalty). It indicates that it is a suitable strategy for refurbishment of existing offices to improve energy efficiency or internal environmental conditions in the summer and should be considered in the design of new offices together with other passive energy efficient strategies.

1. Introduction

Rejection of solar gains is the aim of passive cooling strategies in any type of building and any climatic region. This needs to be balanced with admission of solar heat gains which is beneficial for all building types and climatic conditions; the extent of usefulness is dependent on severity of external conditions and internal heat gains.

Cool materials work by reflecting solar radiation and therefore rejecting solar heat gains at the opaque external surfaces of the building. Heat transfer to the internal space by conduction is therefore reduced; the magnitude of the reduction will be determined by:

- The magnitude of solar radiation.
- The different of air and surface temperature between outside and inside of the building.
- The construction of the opaque building element, namely its resistance to heat transfer.

A number of experimental and computational studies have been carried out to demonstrate the energy benefits of cool roofs in reducing energy demand in buildings in cooling dominated climates. A number of papers have been published for residential buildings [1–6], retail stores [7], and other commercial buildings [8,9]. Work has also been carried out outside the US. A modelling study [10] has shown the benefits in retail store at different cli-

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mates. Cool roofs have also been studied in experimental facilities [11,12].

Experimental and computational studies are less numerous for buildings located in climates with moderate cooling demand because in many cases the heating penalties can out-weight cooling benefits. However, there are net energy benefits to be obtained; in particular cool roofs can improve internal thermal comfort in buildings without air-conditioning. Therefore, they could be considered despite heating energy penalties as they can help avoidance of air-conditioning installation.

Akbari and Konopacki [13] have presented an excellent summary of results to 2004 in the US for both hot and cold regions. Computational studies were carried out to estimate the net direct energy savings (cooling-energy savings minus heat-energy penalties) from reflective roofs on residential and commercial buildings in 11 US metropolitan statistical areas (MSAs). Metropolitan-wide savings were as much as $37M for Phoenix and $35M in Los Angeles and as low as $3M in the heating-dominated climate of Philadelphia.

The same paper [13] presented results for Toronto, Canada. It showed that by increasing the albedo of houses by 0.2 (from moderate-dark to medium-light colour), the cooling-energy use can be reduced by about 30–40%. However, they also found that reflective roofs and shade trees reduce summer cooling-energy use and also potentially increase winter heating-energy use.

A numerical study performed by Shariah et al. [14] for the moderate climate of Amman and the hot climate of Aqaba, in Jordan, showed that by increasing the external reflectance of the roof from 0 to 1, the energy load reduces by 32% for a non-insulated building and 26% for an insulated building in Amann. Higher energy savings are obtained for Aqaba. Synnefa et al. [1] numerically found for various climatic conditions around the world that by increasing the roof albedo by 0.65, cooling reductions of 9–48 kWh/m^2 were obtained, with heating penalties in the range of 0.2–17 kWh/m^2. Furthermore, they concluded that the two most influential factors for the performance of roof reflective coatings are the *U*-value of the roof and the climatic conditions. Akbari et al. [8] conducted experimental and numerical studies for 16 Californian climate zones, and reported energy savings of about 4.5–7.4 kWh/m^2 of conditioned roof area per year. They also differentiated between the investigated buildings, signifying the importance of building operation on the performance of roof reflective coatings.

There is recent interest in the UK's moderate climate on the benefits of cool roofs and an Information Paper was published recently on this [15] arguing that net savings are also obtainable in the UK climatic conditions, with the benefits decreasing with enhanced insulation, lower operating temperatures or increase in internal gains.

In this context, the present paper reports results of work carried out within the framework of the EU project "Cool Roofs" which aims to develop and implement an action plan for the promotion of cool roofs in European countries (www.coolroofs-eu.eu). Part of the project is the implementation of five demonstration projects, as shining examples of cool roofs' capabilities in improving the thermal conditions and reducing the energy consumption in buildings. The case studies were monitored, in regard to their energy performance and indoor environment, before and after the implementation of a cool roof technology. The buildings were selected to achieve maximum geographical and building typology coverage aiming to promote the benefits coming from this technique with reference to cooling energy demand and peak savings all around the EU. The corresponding activities were performed at two levels:

- experimental monitoring in real buildings treated with cool roof techniques (hardware task),
- numerical analysis of the same buildings with a number of variants (software analysis).

In general, the findings of the case studies show 10–40% energy savings and 1.5–2 °C reduction of the indoor temperatures, depending on the climatic conditions [16]. The selected case studies are (a) a school building in Kaisariani, Greece, (b) a laboratory building in the Chania, Crete – Greece, (c) a dwelling in Poitiers, France, (d) a public building (mixed office and laboratory) in Trapani, Italy and (e) an office building in London, United Kingdom (UK). Following the methodology developed by the CoolRoofs Project [16], this paper reports results of the UK case-study. First a description of the building is presented (Section 2), followed by an analysis of the measured data before and after the application of a cool roof (Section 3). In Section 4, the development and calibration of a building model of the case-study is presented, together with the results of a parametric computational analysis to determine the range of application and benefits of cool roofs in offices in London, UK. Measured data were used to calibrate the computational model to improve confidence on its predictions. Summary of results and conclusions are presented in Section 5.

2. Description of the building and cool roof technology

The case-study is the estates office at Brunel University and consists of one open office area and three separate office rooms. It is located on the top floor (flat roof) of a four storey building of which the top floor was constructed in 1995. The total floor area is 137 m^2 of which the open office area accounts for 97.6 m^2. The floor to ceiling height is approximately 2.65 m. The open office area has 6 window openings while each room has one opening. Each of these openings is approximately 0.9 m × 1.5 m. The office has work space for about 15 people but on most occasions there will be about 10–13 working at a time, each provided with a computer.

A survey was carried out to determine the construction details of the roof and walls. The roof is made of 0.15 m thick concrete slab with a 0.04 m insulation layer on top of the slab and is covered with a layer of water proofing material (asphalt). During the second part of the experimental period, the cool roof material was applied on top of the asphalt. The external wall structure is made of 0.125 m thick concrete block work and is protected with 0.18 m insulation layer and ZnAl cladding. The floor is made of 0.15 m thick concrete slab laid with synthetic carpet. All the internal walls are made of dry wall partition. The office has a central heating system with perimeter radiators and is naturally ventilated through openable windows. The windows are fitted with horizontal window blinds. Fig. 1 shows the floor plan and an internal photo of the open plan office and Table 1 summarises the characteristics of the external envelope of the case-study.

The properties of the roof surface relevant to the study of this paper are two: (a) Solar reflectance (SR) or albedo is a measure of the ability of a surface material to reflect solar radiation. The term solar reflectance (SR) designates the total reflectance of a surface, considering the hemispherical reflectance of radiation, integrated over the solar spectrum, including specular and diffuse reflection. It is measured on a scale of 0–1 (or 0–100%). (b) Infrared emittance (ε), is a measure of the ability of a surface to release, absorbed heat. It specifies how well a surface radiates energy away from itself as compared with a black body operating at the same temperature. Infrared emittance is measured on a scale from 0 to 1 (or 0–100%).

The pre-painted building was monitored (roof albedo value 0.1) for two months (May–June 2009); a cool roof paint was applied in July and monitoring continued for another two months (August–September 2009). The cool roof paint was selected from ABOLIN (Cool Barrier 012-CB012) with an SR value of 0.7 and