Energy and Buildings 102 (2015) 172–180

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Effect of the solar radiative properties of existing building roof materials on the energy use in humid continental climates

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ARTICLE INFO

Article history:
Received 28 October 2014
Received in revised form 12 May 2015
Accepted 14 May 2015
Available online 21 May 2015

Keywords:
Solar radiative property
Solar reflectance
Thermal emissivity
Cool roof
Energy savings

ABSTRACT

The use of highly reflective and emissive roof materials can decrease the urban temperature. These cool roof materials might increase the heating demand, while decreasing the cooling demand. In humid continental climates, particularly, increased heating energy might be greater than the saved cooling energy.

In this study, small scale models of each layer's temperature and heat-flux were measured in the winter season and the energy performance was evaluated by the roof's solar radiative properties with various solar reflectance and thermal emissivity values. The cooling, heating, and annual energy consumptions of a detached house were calculated. The energy performance was compared to two types of insulation levels: (i) existing building's insulation level and (ii) insulation level of newly built houses. The results show that the increasing heating demand is more than the saving of the cooling energy demand; however, the annual total energy converted to primary energy decreased by up to 2% due to conversion factor. The heating penalty would decrease by improving the insulation level. New buildings are constructed according to the enhanced design standard, and these buildings may have a cool roof. The designer should carefully consider cool roofs to ensure their optimal application in humid climates.

1. Introduction

Urban heat islands (UHIs), with a warmer urban temperature than the surrounding rural areas, have increased in most urbanized cities. Many cities have been expanded quantitatively with priority to the supply and arrangement of urban infrastructure, change in urban surface, land use, and increasing anthropogenic heat. UHIs increase the urban temperature and contribute to human discomfort [1,2], health problems [3], higher energy consumption [4–6], and pollution [7,8].

Many cities are decreasing the UHIs using the following main strategies: by (1) increasing green area, (2) using cool pavements, and (3) increasing the overall albedo of the city [9]. Green areas include trees, vegetation, parks, and green roofs. Green area can cool an urban area by the evaporation and shading of the urban surface. This cooling effect can moderate temperature and alter the energy balance and cooling load of buildings through shading windows, walls, and rooftop from the incident solar radiation. Green area can decrease the building cooling energy use by 10–60% depending on the climatic zone [2–13]. Cool pavements are reflective or permeable pavements. In the permeable pavements, water passes to the soil through the void or porous materials and evaporates when the temperature increases, contributing to a lower pavement surface [14]. The reflective pavements should be considered with caution when applying them to near-roads buildings. Yaghoobian et al. found that the high albedo pavements with surrounding buildings can increase the peak cooling demand for buildings by 5–10% [15]. High albedo materials can decrease the absorbed solar radiation by building surface and urban structures. Several studies have described the benefits of cool roofs with a high albedo and quantified the energy saving in different building types and climates [16–19]. For hot and mild climates, cool roofs are an effective strategy to reduce the absorbed heat from the sun, whereas in cold climates, cool roofs can be disadvantageous as the heating penalty is higher than the cooling savings. Therefore, cool roofs should be carefully selected for applications in the region with large seasonal temperature differences.

The objective of this study was to quantify the energy use by the solar radiative properties of building surface materials to assess the applicability of cool roofs in humid continental climate. To mitigate the UHIs, new buildings had a limit in the proportion to the entire building stock. The modification of the existing buildings'

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http://dx.doi.org/10.1016/j.enbuild.2015.05.022
0378-7788/

roof property is more effective to mitigate UHI. In this study, only the roof materials are limited as the variables, because roofs have a higher contribution to the UHIs than the walls of a building. The solar radiative properties of typical building roof materials and cool roofs were also investigated. The small scale models' temperature and heat flux were measured in winter days. The materials with various solar radiative properties were applied for energy simulations. The effects of the solar radiative properties of roof materials were parametrically studied considering the energy consumption. In addition, a comparison analysis of the cooling, heating and annual energy consumption of existing house to an newly built house was carried out to evaluate cool roofs can be used without energy penalties.

2. Solar radiative properties of materials

The thermal performance of materials is determined by their surface radiative and thermal properties. The solar radiative properties are characterized by solar reflectance and thermal emissivity; the thermal properties are measured by thermal conductivity and heat capacity and are important for heat storage. Materials with a high heat storage capacity can store more heat when the temperature of the material increases. The solar radiative properties affect the temperature of a surface. The presence of a cool surface on a building would decrease the heat penetration into the building [20]. Akbari et al. reported that the cool roof materials with a high solar reflectance are one of the valuable strategies to mitigate the UHI [21]. Therefore, this study focuses on the solar radiative properties of building materials.

2.1. Solar reflectance and thermal emissivity

Solar reflectance (SR) or albedo is the percentage of solar energy reflected by a surface. The SR value ranges from 0 to 1.0. A value of 0 indicates that the material absorbs all the solar energy, and a value of 1.0 indicates the total reflectance. Building surface materials with a high SR maintain low surface temperatures in sunlight, thereby affecting the use of cooling energy. The SR is measured according to the ASTM E903, ASTM E1918, and ASTM C1549 standards [22–24].

A material's thermal emissivity (TE) determines the heat radiated per unit area at a given temperature with respect to a black body at the same temperature, i.e., with respect to the theoretical maximum emission. TE value ranges from 0 to 1. A true black body has an emissivity of 1. When exposed to sunlight, a surface with a high emissivity will reach the thermal equilibrium at a lower temperature than a surface with a low emissivity, because the high emissivity surface can readily release the absorbed heat energy. The ASTM E 408 or C1371 standard can be used to measure TE [25,26].

The use of cool roof materials with a high SR and high TE values can improve the thermal comfort conditions in the cooling period by reducing the amount of solar radiation absorbed by building envelops and keeping their surface cooler than the regular buildings [16,27]. In particular, in the case of roofs with cool materials, less radiative energy will penetrate the building, thus reducing the cooling load and saving the energy use. However, this can increase the heating load in the winter season. The increase in the heating load may balance the decrease in the cooling load depending on the regional climate and insulation level.

2.2. Solar radiative properties of roof products

Roof products can be divided into eight categories: built-up roof, coating, metal roof, modified bitumen, shingles, single-ply membrane, spray polyurethane foam, and tile. The range of initial SR and TE of 5016 products is listed by their types in Table 1. These properties of the certified roof products are available in the Energy Star website [28]. The properties of the existing roof types have been recently developed. For the cool roof qualification, the roofing materials must meet the minimum SR set by the USEPA Energy Star label and California Title 24; Part 6 [29] has met or exceeded minimum SR and TE [28]. For a low slope roof, the minimum initial SR and aged SR set by the Energy Star is 0.65 and 0.55, respectively. Moreover, the California standard for initial SR, aged SR, and TE

Table 1
Initial solar reflectance and thermal emissivity of roof materials.

Product type	Number of products	Initial SR	Initial TE
Built-up roof	7	0.27–0.80	0.85–0.92
Liquid applied coating	2202	0.25–0.92	0.06–0.96
Metal roof	2514	0.25–0.75	0.06–0.87
Modified bitumen	45	0.25–0.27	0.05–0.88
Shingles	56	0.25–0.66	0.85–0.96
Single-ply membrane	99	0.26–0.83	0.78–0.90
Spray polyurethane foam	2	0.66–0.88	0.88
Tile	91	0.25–0.82	0.67–0.97

Source: Energy Star, www.energystar.gov.

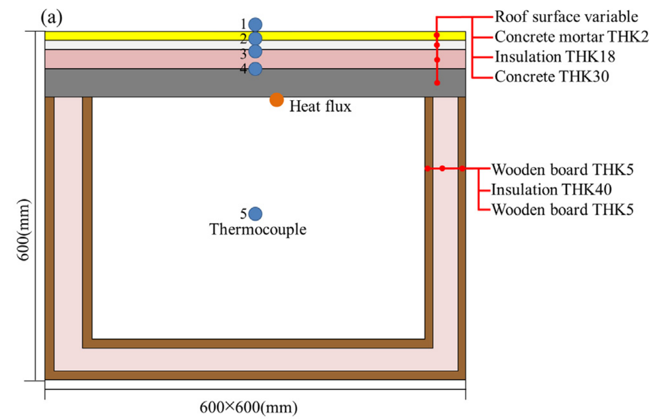

Fig. 1. (a) Outline of the small scale model and (b) three scale models sited on the roof of the university building in Korea.

Table 2
A brief summary of weather data.

Days	Cloud coverage[a] (%)	Average temperature[b] (°C)	Maximum temperature[b] (°C)	Minimum temperature[b] (°C)	Average wind speed[a] (m/s)
1	65	2.4	13.5	−3.8	2.6
2	0	−6.4	6.2	−12.2	5.3
3	34	−4.0	12.3	−14.0	3.1
4	46	1.4	10.7	−4.5	2.8

[a] Source of cloud cover and average wind speed: Korea meteorological administration, www.kma.go.kr.
[b] Source of temperature: field measurement data.