Experimental Study of Cool Roof Impact on Building Performance in Hot-Dry and Dusty Climates

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ABSTRACT

Maintaining thermal comfort in buildings has become a big challenge in developing countries. Cool roof or high reflective/emissive roof reduces absorbed building solar energy, roof surface temperature to reduce energy consumption and maintain thermal comfort. However, the impact on buildings thermal performance located in hot-dry climate and dusty conditions is not well-known. The study presents an experimental and numerical simulation of two identical non-air-conditioned rooms to estimate the impact of cool roof on building performance in dusty conditions of Makkah, Saudi Arabia in the summer season. The results show that the indoor thermal comfort was improved by decreasing the average indoor temperature, underneath roof surface and outside roof surface temperatures by 3.7 °C, 6 °C and 8.9 ° C, respectively. The use of cool roof reduces the energy consumption required for building cooling in clear conditions by about 50 kWh/m2/year. However, dust accumulation decreases the impact of cool roof impact and increases the energy consumption in cooling the building. The study concludes that with the proper roof cleaning process, cool roof is an effective method to improve the indoor thermal comfort and reduce building energy consumption in hot-dry and dusty climates.

INTRODUCTION

Heating, ventilation, and air-conditioning systems (HVAC) consume almost 35% of the world's total energy demand (Seyboth et al. 2008). 85% of the total world building energy consumption is sourced from fossil fuels (Kharseh et al. 2015). Recent studies show that building energy consumption has its implications for the environment (Wong et al. 2010). Building energy consumption is estimated to account for one-third of the global CO_2 gas emissions (Kumanayake and Luo 2018). Although building regulations have been implemented in many countries to reduce energy use, energy consumption is showing an increasing trend in developing countries owing to the lack of regulation enforcement.

In Saudi Arabia, electrical energy consumption has rapidly increased because of the harsh climate conditions. Additionally, the demand for electricity in the Kingdom is increasing owing to the subsidized electricity cost structure and growing population. About 79% of the total energy is nationally consumed by the building sector: residential,

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governmental, and commercial buildings (Almutairi et al. 2015). The energy requirement of the residential buildings amounts to half of this energy consumed. Moreover, the residential electric consumption in the past decade has increased sharply by more than 94%. The high building energy demand is caused by inefficient building envelopes, where about 70% of residential buildings are not insulated, and low air-conditioner energy efficiency ratios (Algarni and Nutter 2013). The high energy demand for residential buildings contributes to greenhouse emission, which in turn has an impact on environment, public health, and global warming (Huang et al. 2018).

Roofs of buildings subject to a high amount of solar incident radiation cause an increase in the roof surface temperature, thereby increasing the cooling load. Therefore, the performance of the building roof needs to be improved to reduce the building energy consumption and CO_2 emissions. The cool roof technology is an efficient way to enhance the roof thermal performance and thermal comfort. The basic principles of cool roof systems under various conditions are summarized by Algarni (2019) and are shown in Figure 1. Many studies have focused on the evaluation of the performance of the cool roof around the world. However, only a few works relate to the hot-dry and dusty climatic conditions of Saudi Arabia. In this study, the impact of the cool roof on the cooling and heating loads of buildings located in hot-dry and dusty climates is studied.

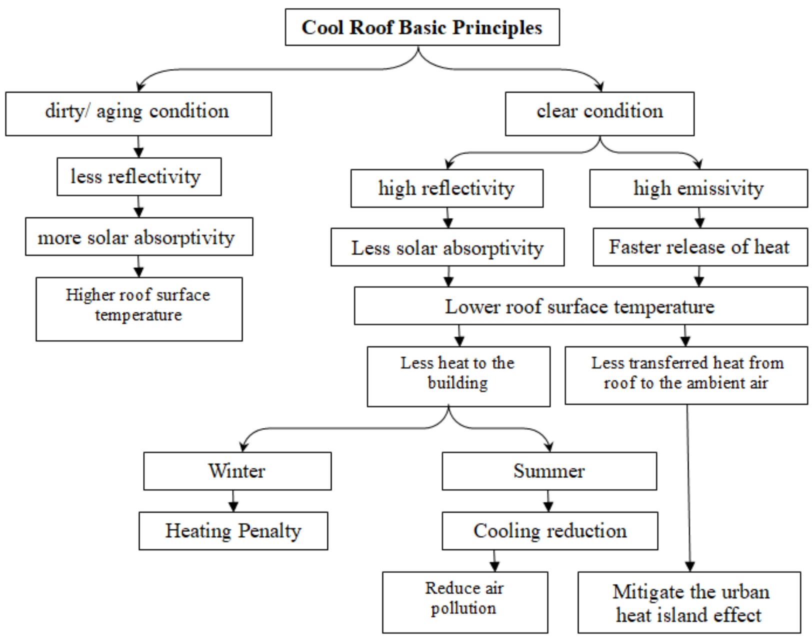

Figure 1 The basic operating principles of cool roof systems under clear and dirty conditions (Algarni 2019).

EXPERIMENTAL TEST ROOM AND BUILDING MODELLING

The experiment and data collection were conducted from June 2018 to August 2018 at a two floor family house located in Makkah, Saudi Arabia as shown in Figure 2. The second floor consists of multi zone rooms where two identical room were selected. The dimensions of each room was 4 (width) × 3.5 (depth) × 3.2 m (height). The thermophysical properties of the building roof are presented in Table 1. All the external walls were three-layered, with the core layer composed of 20 cm thick bricks and plastered on either side. The windows on the east wall were 1 m high and 1 m wide and was made of 2.2 cm thick plywood. The window had no protective overhang. The rooms had a single steel door opening in the north wall, which had a height of 2 m and width of 0.821 m. The door was made of 0.45 cm thick GI metal sheet.

The horizontal roof considered in the study is the most common traditional architecture in Saudi Arabia. A composite horizontal roof of multiple layers as denoted by "N" is shown in Figure 3. The roof's outside surface is exposed to solar absorbed (q_{solar}), convection heat flux (q_{conv}), and sky long wave radiation exchange (q_{sky}). The inside surface of the composite roof is subjected to combined internal convection and radiation heat transfer, (q_i), (Spitler 2010). The (q_i) relates to the load required to maintain the inside room temperature which affected by the solar absorbed (q_{solar}). The cool roof help to reduce the (q_{solar}) because of its high solar reflectivity hence reduce the inside room temperature. The various driving forces involving the heat transfer components, as shown in Figure 3, that may affect the cooling and heating loads were calculated using the heat transfer function method with custom weighting factors. The heat transfer function method implementation involves three phases: calculation the heat gains from solar, conduction and combined internal, calculation of cooling loads as a function of room and other properties, and heat extraction rate. Building envelopes, equipment, and schedule details were used as described in Algarni and Nutter (2013). Typical meteorological year 3.0 (TMY3) was used to simulate the weather condition of Abha. eQuest 3.65 (DOE 2014) was used to simulate the thermal performance of three roof systems: a cool roof (SR = 0.85), dirty roof (SR: affected by dirt accumulation), and typical concrete roof (SR = 0.6). For these roof systems, three roof structures were considered, including a non-insulated roof (U-value of 2.86 W/m² K), poorly insulated roof (U-value of 1.69 W/ m² K), and well-insulated roof (U-value of 0.57 W/m² K) as shown in Table 1.

Figure 2 (a) Southern external wall of the two tested rooms, (b) cool and aged roofs and (c) onsite weather station.

Table 1. Thermo-physical Properties of Roof Materials [Croy and Dougherty 1983]

Material	k (W/m K)	ρ (kg/m³)	c (J/kg K)	Roof U-value (W/ m² K) 2.86	1.69	0.57
				Thickness (mm)		
Cement plaster	0.72	1858	837	15	15	15
Molded polystyrene	0.036	24	1213	0	10	20
Extruded polystyrene	0.029	35	1213	0	0	20
Reinforced concrete	1.73	2243	920	150	150	150
Foam concrete	0.52	1600	837	20	0	0
Membrane	0.19	1121	1675	4	0	0
Sand fill	0.33	1515	800	50	50	40
Mortar bed	0.72	1858	837	15	15	15
Tile	1.73	2243	920	20	0	0

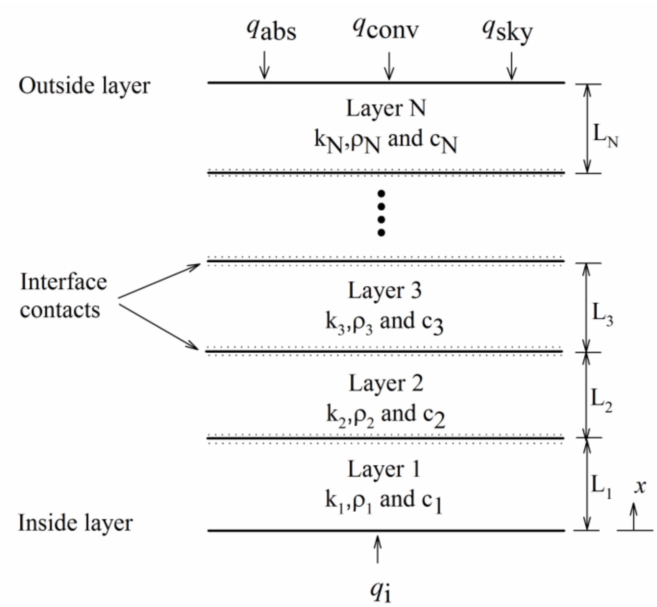

Figure 3 Schematic showing a composite roof in x-direction with multi layers N.

RESULTS AND DISCUSSIONS

Aged roof thermal properties

Classic heat transfer calculations to determine the cooling and heating loads focus on many parameters. However, the building condition changes over time owing to environmental impacts such as accumulated dirt over the roof and its changing radiant properties. In this study, the building roof dirt accumulation was measured during June 2018 to August 2018, as shown in Table 2. A long term dirt accumulation impact, i.e., a month-to-month dirt accumulation, was not considered due to expected periodic cleaning processes such as wind and rain or human cleaning effort. The corresponding roof solar reflectivity was calculated as a function of dirt accumulation. Roof solar reflectivity can be calculated using Equation (1) which is constrained by the following three main conditions; clean, partly dirty, or fully dirty as shown in Equation (2) (Algarni and Nutter 2015).

$$\lambda = \lambda_{new-roof} + \frac{1.5M}{\rho_p \times d_p} f(\lambda_{dust} - \lambda_{new-roof}) \quad (1)$$

$$if \;\; A \left(= \frac{1.5M}{\rho_p \times d_p} f \right) = \begin{cases} 0 \\ (0,1) \Rightarrow \\ \geq 1 \end{cases} \begin{cases} \lambda = \lambda_{new-roof} \\ Calc.\ \lambda \\ \lambda = \lambda_{dust} \end{cases} \quad (2)$$

As shown in Equation (2), in clear conditions, i.e., there is no dirt covering the roof (*A=0*), roof solar reflectivity is equal to the reflectivity of new roof. In partly dusty conditions, roof solar reflectivity can be calculated using Equation (1). Finally, when the roof is completely covered by dust (*A≥1*), roof solar reflectivity is equal to dust reflectivity.

Table 2. Monthly Dirt Accumulation and Corresponding Calculated Roof Reflectivity of a Dirty Roof

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Dirt (g/m^2)	8.9	11.3	18.2	19.4	16.9	23.2	31.9	29.3	14.5	9.4	6.4	5.7
Reflectivity	0.64	0.31	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.36	0.44	0.45

Cool roof impact on thermal performance of building

Because of the climatic conditions, 73% of the consumed electricity is attributed to air-conditioning during the peak summer, which is three times as much as the winter average. The monthly electricity consumption of a non-insulated building as a function of the average ambient temperature is presented in Figure 4. This data reveals a trend between the monthly electricity consumption and the average ambient temperature because the electricity consumption is primarily affected by the high use of air-conditioning as a result of the ambient temperature.

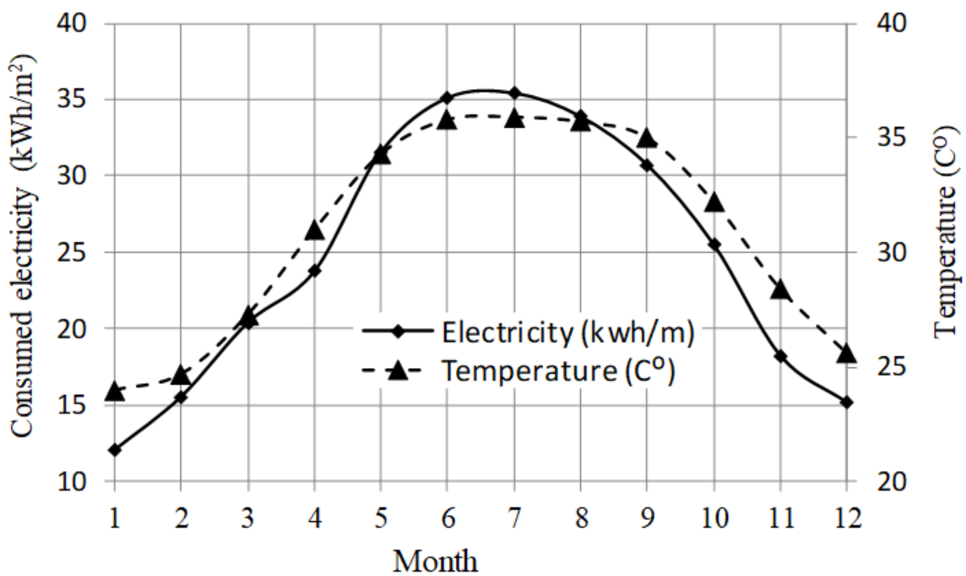

Figure 4 Electricity consumption as a function of average ambient temperature.

To examine the impact of the cool roof, the roof surface of one room was painted with white cool paint and kept clean using compressed air cleaning system, whereas the other room roof was left as is (light concrete). Next, three thermocouples were fixed: on the top and underneath of cool and concrete roofs and 1 meter below the internal roofs for both rooms for the month of June 2018. The ambient temperature and incident roof solar irradiation were measured using an onsite weather station. By applying the cool roof (white paint), the indoor thermal comfort was improved because of a decrease in the average daily indoor temperature. The results show that the indoor thermal comfort was improved by decreasing the average indoor temperature, underneath roof surface and outside roof surface temperatures by 3.7 °C, 6 °C and 8.9 ° C, respectively. The measured temperatures are shown in Figure 5.

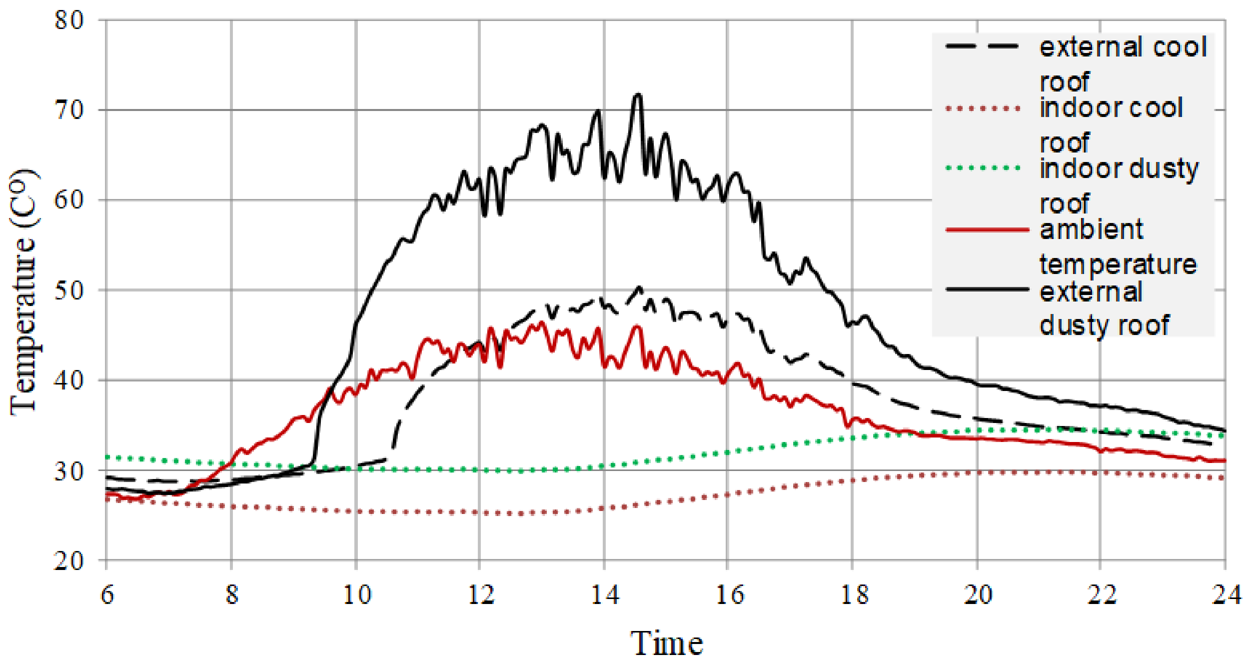

Figure 5 Roof measured temperatures: external cool roof, external dusty roof, indoor cool roof, indoor dusty roof, ambient temperature.

Annual building cooling and heating loads were calculated for the concrete roof as a reference case to evaluate the impact of the cool roof on the thermal performance of the building. The lateral heat flow from unpainted sections to the painting roof was not considered. Results of the annual cooling load, annual heating load, and peak roof conduction for three roof systems considering three U-values are summarized in Table 3. For all cases, building cooling energy consumption is dominant compared with the heating power consumption. For the non-insulated concrete roof (U-value = 2.86 W/ m² K), the electric energy consumptions for building cooling and heating are 298.9 and 48.0 kWh/m²/year, respectively, compared to 252.3 and 22.5 kWh/m²/year for cooling and heating in the case of the well-insulated roof (U-value = 0.57 W/ m² K).

Table 3. Calculated Annual Cooling and Heating Loads, and Peak Conduction

	Concrete roof (λ=0.6)			Dirty roof (λ=f(M))			Cool roof (λ=0.85)		
U-value (W/m² K)	Annual cooling (kWh/m²)	Annual heating (kWh/m²)	Peak cond. (W/m2)	Annual cooling (kWh/m²)	Annual heating (kWh/m²)	Peak cond. (W/m²)	Annual cooling (kWh/m²)	Annual heating (kWh/m²)	Peak cond. (W/m²)
2.86	298.9	48.0	54	420.6	44.9	110	246.4	49.3	32
1.69	278.2	34.9	36	358.5	33.2	66	243.0	35.7	22
0.57	252.3	22.5	11	282.1	21.9	24	239.2	22.7	7

It was found that the net building annual cooling consumption decreased owing to the high solar reflectiveness of the cool roof; whereas the net annual heating load increased slightly. The cool roof for non-insulated, poor, and well-insulated concrete roofs resulted in a reduction in cooling consumption, ranging from 30.1 to 52 kWh/m²/year. The maximum annual heating load penalty incurred because of the cool roof was only 1.3 kWh/m², a negligible amount compared to the annual cooling cost savings. The peak roof conduction decreased by 16 kWh/m²/year compared to the typical roof. However, in dirty roof conditions, accumulated dirt may reduce the performance of the cool roof because of its high solar absorptivity, especially for the non-insulated roof. As shown in Table 3, the annual cooling loads in the non-insulated roof reached 420.6 kWh/m^2.

CONCLUSIONS

In this study, the impact of the cool roof on the thermal performance of buildings located in the hot-dry and dusty climates of Makkah, Saudi Arabia was studied. The results showed that the use of the cool roof reduced the energy consumption required for building cooling by about 52.5 kWh/m^2/year; whereas the maximum increase in energy consumption owing to the winter heating was about 3.1 kWh/m^2/year. The indoor thermal comfort was improved as the average indoor temperature was decreased by 3.7 °C. The study concludes that the cool roof is an effective method to improve the indoor thermal comfort and reduce energy consumption of buildings located in Makkah, Saudi Arabia and places with similar climatic conditions.

NOMENCLATURE

A = a ratio of roof unit area covered by dust
$c_{1,...,N}$ = roof layers thermal capacities (J/kgK)
d_p = mean dust diameter (m)
f = packing factor, 0.91for hexagon packing
$k_{1,...,N}$ = roof layers thermal conductivities (W/mK)
$L_{1,...,N}$ = roof layers thickness (m)
M = accumulated dust (kg/m^2)
N = roof multiple layers
q_{conv} = outside roof heat convection (W/m^2)
q_i = combined internal heat transfer (W/m^2)
q_{sky} = sky long wave radiation (W/m^2)

Greek

λ = solar reflectivity
$\lambda_{new\text{-}roof}$ = new roof solar reflectivity
λ_{dust} = dust solar reflectivity
ϱ_p = dust density (kg/m^3)
$\varrho_{1...N}$ = roof layers densities (kg/m^3)

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