Journal of Building Engineering 2 (2015) 52–58

Contents lists available at ScienceDirect

Journal of Building Engineering

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

Optimizing roof insulation for roofs with high albedo coating and radiant barriers in India

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ARTICLE INFO

Article history:
Received 13 November 2014
Received in revised form
19 February 2015
Accepted 14 April 2015
Available online 15 April 2015

Keywords:
Radiant barriers
Cool roofs
Insulation thickness optimization
Energy simulation
Internal rate of return

ABSTRACT

To make roofs energy efficient, typically two types of techniques are followed: surface treatments (cool roofs, radiant barriers) and thermal property modifications (roof insulation). The interplay between these two techniques has been studied using energy simulations. A single storey, daytime operational, office building of 200 m^2 area has been simulated for five climatic zones in India. A total of 88 different roof combinations have been studied for each climatic zone. An economic analysis using Internal Rate of Return has been performed to identify a suitable roof insulation thickness for a roof with high albedo, and radiant barrier combination. The incremental benefits in energy savings reduces by adding insulation after a limit. For a roof with albedo of 0.6 and radiant barrier emittance of 0.2, the optimized roof *R*-value is 0.49 m^2 K/W in hot and dry and composite climates, 0.31 m^2 K/W in warm and humid and temperate climates, and 1.02 m^2 K/W for cold climates.

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1. Introduction

India is a tropical country with an average annual solar insolation between 4000 and 7000 Wh/m^2 day [1]. This leads to high outdoor dry bulb temperature and higher cooling energy consumption in daytime operational buildings. Therefore, building envelope plays a very important role in reducing the cooling energy consumption of a building. Among various envelope components, roofs receive the maximum direct solar radiation [2]. So it is important to have an efficient roof to reduce the energy consumption of a building.

Fig. 1 shows the heat transfer in a roof. Part of the solar radiation reaching the roof surface is absorbed and the rest is reflected back. Part of the absorbed solar radiation is re-radiated back to the atmosphere, part of it is conducted in to the building and a part of it is lost in convection to the atmosphere. The heat reaching the inner surface is distributed by convection and radiation.

There are three solutions to reduce the heat transfer into the building. They are roof insulation, cool roofs, and radiant barriers. Though roof insulation is common in India, cool roofs and radiant barriers are relatively new solutions. Cool Roof Rating Council (CRRC) defines cool roofs as "any roof that reflects and emits the sun's heat back to the sky instead of transferring it into the building below" [3]. Radiant barriers is a way of increasing the thermal performance of a roof by introducing a new layer with low emissivity below the roof surface [4]. The materials that are used as radiant barriers are characterized by a far infrared emittance of 0.1 or less [5]. Far infrared is a region in the infrared spectrum of electromagnetic radiation defined as any radiation with a wavelength of 15–100 μm.

Many studies have been performed world-wide to understand the benefits of these three solutions. Various studies have highlighted the benefits of roof insulation [6–9]. Some of the noteworthy findings indicate that insulation can lead to increase in energy consumption under certain circumstances. D'Orazio et al. [6] state that over use of insulation can result in adverse effects. In their study conducted for a Mediterranean climate (Italy), it was found that over use of insulation reduces the effectiveness of traditional passive strategies and reduces indoor thermal comfort. Further, it leads to "box effect" in which the solar radiation entering the building through transparent surfaces becomes the heat sources inside the building during nights.

Halwaura et al. [7] show that insulated roof slabs could have a desirable behaviour with respect to life cycle performance in addition to providing other benefits such as cyclone resistance and higher robustness to the building.

Another simulation study by Masoso et al. [8] on wall insulation for a building in Botswana concluded that insulation is not always suitable to reduce the cooling energy of a building. There exists a point for a given set of cooling set points, internal gains, when the building switches from "lower the *u*-value the better" to

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http://dx.doi.org/10.1016/j.jobe.2015.04.004
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Nomenclature

ACH	air changes per hour
CDD	cooling degree days
CoP	coefficient of performance
CRRC	Cool Roof Rating Council
HDD	heating degree days
HVAC	heating ventilation and air conditioning
IRR	Internal Rate of Return
MARR	minimal attractive rate of return
PTAC	packed terminal air conditioning system
R value	thermal resistance
SR	solar reflectivity

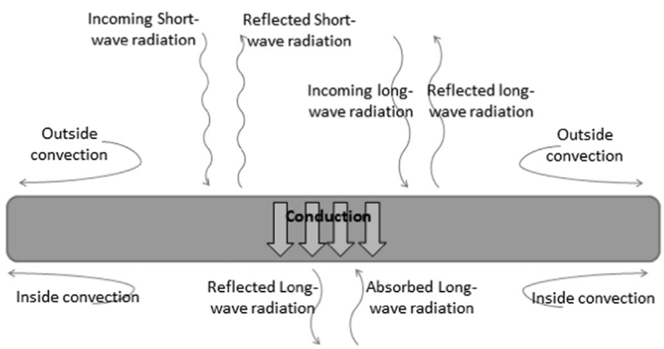

Fig. 1. Heat transfer in a roof.

“higher the *u*-value the better”. This is known as the “point of thermal inflexion”.

It is possible that the combined use of cool roofs, radiant barriers, and roof insulation can lead to an early occurrence of the point of thermal inflexion. Therefore, it is necessary to perform a combined analysis to find the optimal combination of cool roof, insulation, and radiant barriers.

Akhbari et al. [10] have studied the effect of roof reflectivity on different roof insulations for residential buildings. A parametric simulation for four different duct insulations, five different ceiling insulations, and four different levels of roof reflectivity over 32 different climatic regions was performed. The results show that for hot climates, increasing the roof reflectivity from 20% to 60% is worth over half of the roof insulation that is required for 20% reflectivity.

Another study by Akbari et al. [11] for commercial buildings was performed to find adjustment factors for roofs with high reflectivity to reduce the insulation levels. These adjustment factors were computed in a way that the net energy use of the building remains constant when compared with the energy use of a dark-coloured roof with insulation. Simulations were performed over DOE-2 prototype buildings over 19 different climate bins. The roof reflectivity varied from 5% to 75% with three different insulation levels.

Gentle et al. [12] studied the 18 different combinations or roof reflectivity and *R*-value of the roof over a temperate climate. The analysis focused on cooling months over the total cooling energy consumption and the peak energy consumption. The results show that moderately *R* value of 1.63 m^2 K/W is superior to high *R* value unless a roof is dark or the winter heating demand is high.

Though various studies have pointed out that highly reflective roofs have a lesser insulation requirement, the effect of radiant barrier and cool roof on insulation is studied for Indian climatic zones. In this study, different combinations of cool roof, radiant barriers, and roof insulation have been analysed for five different climatic zones of India as described in the National Building Code of India [13].

2. Methodology

2.1. Simulation model

EnergyPlus V7.1 was used to create a model of an office building for this study. The model is a single storey building with core plus perimeter zones. The total roof area is 200 m^2. The schedules are used as per a typical daytime operational building. The model has a window to wall ratio of 30% and a floor to ceiling height of 3.5 m. Windows are equally distributed across all four walls. The materials and the internal loads taken in the model are as per Energy Conservation Building Code of India. (Bureau of Energy Efficiency, 2007). The building is completely air conditioned with an air infiltration rate of 0.1 ACH in the core zone and 0.2 ACH in the perimeter zone. The air conditioning system taken in the building is a Packaged Terminal Air Conditioning System with a cooling CoP of 3.0 and electrical heating with a CoP of 1.0. Details of the model and the schedules are given in Tables 1 and 2 (Fig. 2).

2.2. Variations for parametric analysis

The parametric simulation was carried out for different roof insulation levels, cool roof reflectivity, and thermal emittance of radiant barriers. The insulation considered here is an over deck insulation, which has thermal properties similar to commercially available Styrofoam. The thermal conductivity of the insulation is

Table 1
Input details of the simulation model.

General information	
Building type	Office
Location	5 Different climates as per National Building Code
Geometry	14.14 m × 14.14 m
Number of zones	5 (4 Perimeter + 1 core)
Floor area	200 m^2
Activity and internal loads	
Occupancy	From 9:00 to 17:00
Zone floor area per person	14 m^2/person
Lighting power density	10.8 W/m^2
Electric power density	16.15 W/m^2
Infiltration	Core zone – 0.1 ACH perimeter zone – 0.2 ACH
Construction	
Wall *u*-value	0.44 W/m^2 K
Openings	
u Value of fenestration	3.3 W/m^2 K
SHGC	0.25
Light transmission	0.2
HVAC	
HVAC system type	PTAC
Heating CoP	1.0 (Electrical)
Cooling CoP	3.0 (Electrical)
Heating set point (°C)	20
Cooling set point (°C)	25
Heating set back (°C)	10
Cooling set back (°C)	40

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