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Investigation of cooling load reduction in buildings by passive cooling options applied on roof

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ABSTRACT

Performance of three passive cooling systems namely, water pond on roof, water jacket on roof and radiation shield on roof is assessed here experimentally and numerically. In each case a mathematical model of the building was developed by taking into account the time-varying conduction, convection and radiation heat loads as well as infiltration heating load, aiming to provide both an acceptable accuracy and reasonable computational time. The numerical results were then validated against the experimental data taken from a model house, which was build and tested in Shiraz, Iran. The experimental and numerical results indicate that the application of these passive cooling methods can reduce the cooling loads required during the summer considerably. Furthermore, to compare the performance of these techniques, the temperature inside the building and the cooling load required to maintain a constant temperature inside the building were calculated. The calculated results indicate that among the assessed passive techniques water pond and water jacket on roof have the best and the lowest performance, respectively.

1. Introduction

Recently the interest in energy-efficient buildings is on the rise globally, due to the increase in both the price of energy and the concern about the global warming. In an energy-efficient building the passive cooling/heating systems are employed to decrease the energy consumption of the buildings. Passive cooling relies on controlling and dissipating of the solar radiation heat and thermal gain during the hot seasons, while the passive heating applies the solar thermal energy to warm inside the building during the cool seasons. Roof, windows, walls and the orientation of the building are the key components in the passive cooling/heating of a building. However, among these parameters, roof provides a great potential for passive cooling, due to its large surface area exposed to sky, which both receives the largest fraction of the solar radiation and provides a large surface for heat loss [1]. Therefore the overall aim of the current work is to investigate the effect of different passive cooling techniques applied on the roof of a typical house.

Different passive cooling systems applied to building roofs have been proposed so far such as water pond on roof, in which the latent heat of evaporation is applied for cooling [2], heat dissipation techniques, in which the radiation heat gained by the roof is decreased through reduction of the incident radiation [3] and water jacket on roof that uses nocturnal and convection cooling [1,4]. These methods have been the subject of many researches over the past years. Sodha et al. [5] showed that the heat flux coming into a room through the roof can be reduced by approximately 48% using an open water pond on roof in Delhi. Raeissi and Taheri [6] developed a numerical model to predict the thermal performance of a building with shaded water pond, water pond and shaded roofs in Shiraz, Iran. They found that the best passive cooling performance can be achieved through shaded water pond, followed by the water pond and shaded roof. Yadav and Rao [7] proposed a theoretical model to predict the thermal performance of a building with water pond on roof, in which the evaporation from water surface together with the thermal mass of water is employed to regulate the building temperature. They indicated that the indoor temperatures of a building located in Delhi can be maintained below 30 °C in summer through application of water pond on roof, while the maximum dry-bulb temperatures are above 40 °C. Several passive modifications including white painted roof, insulated roof, water pond on roof and evaporative cooling using a layer of wet gunny bag cloth on roof were assessed by Amer [8]. The results show that the inside air temperature falls to within 6 and 3 °C, respectively, from the ambient temperature when the ceiling is painted white, or provided with a layer of thermal insulation. He also found that evaporative cooling leads to the best cooling effect among the

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Nomenclature

A	area (m^2)
α_D	absorptivity for diffuse radiation
$\alpha_{wd,I}$	absorptivity of glass for direct radiation
$\alpha_{wd,D}$	absorptivity of glass for diffuse radiation
C_F	cloud factor
Cp_{wt}	specific heat of water ($J\,kg^{-1}\,{}^{\circ}C^{-1}$)
D_{eq}	equivalent diameter (m)
D_h	diffuse solar radiation ($W\,m^{-2}$)
ε_P	emissivity of plastic cover
ε_R	emissivity of roof surface
ε_W	emissivity of walls
ε_{wt}	emissivity of water
F	shape factor
$f(t)$	the diurnal radiation heat flux
H	distance between the radiation shield and the surface of the roof (m)
h_i	inside convective heat transfer coefficient ($W\,m^{-2}\,{}^{\circ}C^{-1}$)
h_∞	outside convective heat transfer coefficient ($W\,m^{-2}\,{}^{\circ}C^{-1}$)
I_h	direct solar radiation ($W\,m^{-12}$)
k	conductivity of roof ($W\,m^{-1}\,{}^{\circ}C^{-1}$)
m_{wt}	mass of water (kg)
Q_{AI}	heat transfer due to infiltration (W)
$\dot{Q}_{c,j}$	the cooling load for the building with the j passive cooling method (W)
$\dot{Q}_{c,ord,roof}$	the passive cooling load required for a building with an ordinary roof (W)
Q_L	total heat transfer due (W)
Q_W	heat transfer through walls (W)
Q_{wd}	heat transfer through window (W)
Q_R	heat transfer through the roof (W)
q_D	diffuse solar radiation reach the roof with shield on it (W)
q_I	direct solar radiation reach the roof with shield on it (W)
q_{sky}	radiation from sky (W)
q_{vap}	heat transfer of pond due to evaporation (W)
$q_{wt,R}$	heat transfer from water to roof (in pond on roof and jacket on roof) (W)
$q_{wt,\infty}$	heat transfer from water to ambient (in pond on roof and jacket on roof) (W)
T	temperature of walls and roof (°C)
T_i	model house inside temperature (°C)
T_{sky}	sky temperature (°C)
T_∞	ambient temperature (°C)
T_{wd}	window temperature (°C)
T_{wt}	water temperature (in pond on roof and jacket on roof) (°C)
$\tau_{wd,I}$	transmissivity of glass for direct radiation
$\tau_{wd,D}$	transmissivity of glass for diffuse radiation
τ_{wt}	transmissivity of water (equivalent of water and plastic cover in pond on roof and jacket on roof UNCLEAR!)
U	overall heat transfer coefficient ($W\,m^{-2}\,{}^{\circ}C^{-1}$)
χ_{cJ}	ratio of resulted heat load using 'J' option on roof to heat load using ordinary roof
z	distance from inside surface in the walls or roof (m)
θ_z	zenith angle (rad)

Letters

R	roof
w	wall
wd	window
wt	water
∞	ambient
S	solar
sky	sky
i	inside
in,exp	experimental data for inside
out,exp	experimental data for outside
cal	calculated data
$ord,roof$	ordinary roof
$sh,roof$	radiation shield on roof
$pd,roof$	water pond on roof
$jkt,roof$	water jacket on roof

assessed passive methods, followed by the solar chimney, which leads to an inside temperature within 1 °C of the ambient temperature. Wanphen and Nagano [9] investigated the performance of four kinds of roof materials namely pebbles, silica sand, volcanic ash and siliceous shale, to determine those that can moderate the roof surface temperature more effectively using their humidity and evaporative cooling effect. They assessed these materials against their moisture absorption and evaporation capabilities and found that porous materials can satisfactorily lower the roof surface temperature. Among the tested samples, large and small particle of siliceous shale were found to lower the daily average roof surface temperature by up to 8.6 °C and 6.8 °C, respectively. The effect of tree-shading on thermal performance of the buildings has been also investigated by Balogun et al. [10]. Juanico [11] proposed a simple, economic and practical design of a roof integrated with water solar collectors, in which the received solar heat flux on the surface of the roof is mitigated by the solar collectors due to the change in the roof configuration. He showed that this concept can lead to the design of low-cost roofs which also provide passive cooling. The use of a corrugated aluminum sheet together with a layer of polyurethane for both dissipation and reduction of the received solar heat flux on roof was studied by Alvarado and Martinez [12]. They showed that the roof insulation system can reduce the cooling load significantly. Hay and Yollet [1] proposed the application of sealed plastic bags of water, as water jackets on roof, where the high specific heat capacity of water is used to moderate the temperature inside the building. They found that the use of water pond on roof regulates the daily variations of the temperature inside the building. Furthermore, they showed that the cooling effect of the plastic bags is attributed to their nocturnal radiation to the sky at nights. Meng and Hu [13] studied the application of a humid porous medium on roof to reduce the temperature of the outer surface of the roof through evaporative cooling. A comprehensive review of the passive heating/cooling systems, reporting the main advantages and disadvantages of these methods up to 2011 has been published by Spanaki et al. [14]. Thermal performance of various passive cooling methods for buildings in arid regions was assessed by Nahar et al. [15]. Recently, Yang et al. [16] examined evaporation and cooling of a shallow water reserve on roof. A number of studies have also assessed the effect of roof color on the thermal performance of the building [17–20]. Museli [21] presents low-cost radiative materials to limit the heat gains during diurnal cycle for hot seasons. However, despite the large number of proposed and assessed systems for passive heating/cooling, the efficiency of the most of these techniques has not been investigated thoroughly in Iran yet, whilst the efficiency of a passive heating/cooling system