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Impact of external longwave radiation on optimum insulation thickness in Tunisian building roofs based on a dynamic analytical model

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HIGHLIGHTS

- An efficient tool is proposed for a rigorous energy analysis of building envelope.
- The longwave radiation has an important impact on the energy requirements.
- Optimum insulation thickness for roofs is rigorously determined in a cost analysis.
- The present method is more accurate than the sol–air degree hours method.
- The proposed model is applicable to the study of the efficiency of cool roofs.

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ABSTRACT

In Tunisia, the building sector is considered as a major issue of energy consumption. A special attention should be drawn to improve the thermal quality of the building envelope with real consideration of the Tunisian climate specificity. One of the most effective measures is the roof insulation. Therefore, the present study is concerned with the determination of the optimum insulation thickness and the resulting energy savings and payback period for two typical roof structures and two types of insulation materials. An efficient analytical dynamic model based on the Complex Finite Fourier Transform (CFFT) is proposed and validated in order to handle the nonlinear longwave radiation (LWR) exchange with the sky. This model provides a short computational time solution of the transient heat transfer through multilayer roofs, which could be a good alternative to some numerical methods. Both heating and cooling annual loads are rigorously estimated and used as inputs to a life-cycle cost analysis. Among the studied cases, the most economical one is the hollow terracotta-based roof insulated with rock wool, where the optimum insulation thickness is estimated to be 7.9 cm, with a payback period of 6.06 years and energy savings up to 58.06% of the cost of energy consumed without insulation. The impact of the LWR exchange component is quantified and the results show its important effect on the annual transmission loads and, consequently, on optimum insulation thickness. A sensitivity analysis shows the efficiency of cool roofs in the Tunisian climate context, where the cooling energy cost benefits outweigh the wintertime penalty. Comparison of CFFT results with those of sol–air Degree-Hours (DH) shows that optimum insulation thickness and energy savings are overestimated and payback period is underestimated using the latter model. The proposed CFFT model could be an efficient tool for the design and the energy analysis of building envelope components in various climatic locations.

1. Introduction

In Tunisia, the housing stock has experienced a strong growth over the last three decades at an annual rate of about 3% [1]. Due to this increase, the building sector is actually the first energy consumer with 37% of the national energy consumption [2]. The upward trend in energy demand in this sector is also related to the population growth and the improvement of household living standards resulting in a rising demand of higher comfort levels.

In the Tunisian climate, both heating in winter and cooling in summer are required to reach comfort levels [3]. However, in recent constructions there is no real consideration of environmental conditions, including large temperature differences between summer and winter, nor special attention to improve the thermal

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Nomenclature

A_s	annual energy savings (TND/m^2)
b	payback period (years)
C_{el}	cost of electricity (TND/kWh)
C_{enr}	cost of energy consumption (TND/m^2)
CFFT	Complex Finite Fourier Transform
C_g	cost of natural gas (TND/m^3)
C_i	cost of insulation material in (TND/m^2)
C_{ins}	cost of insulation material in (TND/m^3)
C_t	total cost (TND/m^2)
COP	coefficient of performance of air-conditioning system
d	discount rate (%)
DD	Degree-Days (°C days)
DH_c	cooling Degree-Hours (°C h)
DH_h	heating Degree-Hours (°C h)
EP	EnergyPlus software
EPS	expanded polystyrene
h	heat transfer coefficient (W/m^2 K)
H_u	heating value of natural gas (J/m^3)
i	complex argument, inflation rate (%)
k	thermal conductivity (W/m K)
k_{ins}	thermal conductivity of insulation material (W/m K)
L	layer thickness (m)
L_{ins}	insulation thickness (m)
L_{opt}	optimum insulation thickness (m)
LWR	longwave radiation
n	lifetime of building (years)
N	number of layers of composite roof
NIM	National Institute of Meteorology
p	period (h)
PWF	Present Worth Factor
q	heat flux density (W/m^2)
Q_c	yearly cooling transmission loads (J/m^2)
Q_h	yearly heating transmission loads (J/m^2)
RW	rock wool
t	time (s)
T	temperature (K)
TND	Tunisian Dinar (1 TND = 0.49 US$)
U	overall heat transfer coefficient (W/m^2 K)
U_{wt}	overall heat transfer coefficient without insulation layer (W/m^2 K)
V	velocity (m/s)
x	coordinate direction normal to roof (m)

Greek symbols

α	thermal diffusivity (m^2/s)
ε	emissivity
η_s	efficiency of the heating system
λ	solar absorptivity
σ	constant of Stefan Boltzmann (W/m^2 K^4)

Subscripts and superscripts

abs	absorbed
c	convective
i	inside
j	layer number
m	Fourier transform coefficient
o	outside
r	radiative
s	surface, solar

quality of the building envelope. Current predictions show a rapid increase in the stock of air-conditioners of about 30% per year until saturation [4]. In addition, and due to the promotion of the natural gas by the Tunisian government, the percentage of households equipped with gas central heating systems will reach about 40% in 2030 versus 2% observed in 2004 [4].

Hence, the building sector is considered today as a major issue of energy consumption. One of the most effective measures in the Tunisian climate context is the roof insulation. Indeed, the roof is the envelope component which receives the most solar radiation in summer and which contributes significantly to heat losses in winter. The optimum insulation thickness is the value that provides the minimum total cost, including the insulation cost and the energy consumption cost over the lifetime of the building.

The annual heating and cooling transmission loads are the main inputs required in the analysis of optimum insulation thickness and should be rigorously evaluated. In the exterior surface heat balance, the net longwave radiation (LWR) exchange between the surface and its surroundings plays an important role in the accurate evaluation of thermal losses through the building envelope [5]. However, this heat component is often considered of secondary importance compared with solar radiation and convective exchange. It has been shown that about 20% of the heat losses that occur during the heating period are resulted from the LWR heat exchange between the building envelopes and the environment [6]. Cole [7] presented a review where he discussed the nature of the LWR environment and explained the origins and characteristics of the equations that quantify it. More recently, Evins et al. [8] implemented improvements to the LWR process in the EnergyPlus simulation engine. Their new approach calculations resulted in a decrease of 18% in the heating loads and an increase of 19% in the cooling loads. Ibrahim et al. [9] linearized the LWR heat exchange equation and used a constant value of the outside radiative heat transfer coefficient. They compared measured values of the outside surface temperature of exterior walls to values simulated with and without LWR, and showed the cooling effect of the sky, notably during the nights. Al-Sanea et al. [10] accounted for the nonlinear LWR exchanges with the sky and the ground with refined means for estimating the sky temperature, in order to determine the optimum insulation thickness for cavity walls. Among all the configurations and insulation materials considered, a 9-cm-thick molded polystyrene layer with no air space is found to be the most economical. Periodic changes in the nonlinear LWR exchange were considered in Refs. [11–13] using a more simplified sky temperature model. On the other hand, the outside LWR component has been neglected by many researchers and overly simplified by others.

In most of the studies, the estimation of building heating and cooling loads is based on the Degree-Days (DD) concept which assumes that the energy requirement is proportional to the difference between the indoor base temperature and the mean outdoor air temperature [14–18]. This method provides a simple estimation of annual loads, but does not consider the impact of the solar radiation, the LWR exchange, the building materials, the surface properties and the orientation on the energy balance of a building component [19]. In other studies [20–23], the sol–air temperature [24,25] was used instead of the outdoor ambient air temperature for calculating heating and cooling DD. The concept of sol–air DD, accounts for the combined effect of the incident solar radiation, convection with ambient air and LWR exchange with the sky and the surrounding surfaces. However, several published works considered the effective sky temperature equal to the ambient air temperature [26–28], or adopted a constant value of the temperature correction factor, as suggested by ASHRAE [29–31].