Energy Conversion and Management 76 (2013) 674–684

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermal, economical and environmental analysis of insulated building walls in a cold climate

Meral Ozel *

Department of Mechanical Engineering, Firat University, 23279 Elazığ, Turkey

ARTICLE INFO

Article history:
Received 21 May 2013
Accepted 10 August 2013

Keywords:
Dynamic thermal conditions
Heating transmission load
Optimum insulation thickness
Energy savings
Fuel consumption and emissions

ABSTRACT

In this study, thermal, economical and environmental effects in insulated building walls are numerically investigated under dynamic thermal conditions for two different wall structures and two different insulation materials. The investigation is carried out for different wall orientations during the winter period in Kars city which is one of the coldest cities of Turkey.

For this purpose, a computer model based on an implicit finite difference procedure, which has been previously validated, is used under steady periodic conditions. Firstly, thermal characteristics such as yearly heating transmission load, yearly averaged time lag and decrement factor are calculated for heating season. The results show that maximum time lag, minimum decrement factor and lowest heating load are obtained in the brick wall with XPS (Extruded polystyrene) while minimum time lag, maximum decrement factor and highest heating load are obtained in the concrete wall with EPS (Expanded polystyrene).

Secondly, yearly heating loads obtained under dynamic conditions are used as inputs to an economic model for the determination of the optimum insulation thickness. The optimum insulation thicknesses, energy savings and payback periods are calculated by using life-cycle cost analysis over lifetime of 20 years of the building. For heating season, it is seen that the lowest value of heating load, optimum insulation thickness and energy saving is obtained for the south-facing wall while highest value of them is obtained for the north-facing wall. The results show that for heating season, the most economical orientation is south-facing wall with an optimum insulation thickness of 9.2 cm at brick wall with XPS.

Lastly, fuel consumption and emissions of CO_2 and SO_2 are calculated by taking into consideration wall orientations for different structure and insulation materials. It is seen that as the insulation thickness increases, the yearly heating transmission load and consequently, fuel consumption and emissions decrease. The results show that for 9 cm insulation thickness, this decrement is 85% for all oriented walls.

1. Introduction

The most important part of energy strategy of a country is energy saving. Because of the limited energy sources and environmental pollution coming from using the fuels, energy saving has become compulsory [1]. Energy consumption is rapidly increasing due to the population increase and urbanization. The energy consumption is distributed among four main sectors: industrial, building (residential/commercial), transportation and agriculture. The building sector is the largest energy consumer following the industrial sector [2]. Buildings are large consumers of energy in all countries. In regions with harsh climatic conditions, a substantial share of energy consumption and the consequent environmental pollution are attributed to space heating of residential buildings. The proper design and selection of building envelope and its components is an efficient means to reduce the space heating load. Notable among them is selecting well-insulated exterior walls to reduce energy consumption and greenhouse gas emission [3]. Insulated building walls are integrated parts of a building envelope. They protect the inner space from extreme weather conditions and damp down large fluctuations in temperature. As such, the building envelope should provide the necessary thermal comfort for the occupants as well as reduce energy consumption requirements for cooling and heating. This is usually done through increasing thermal resistance of this envelope and, hence, reducing transmission loads. Therefore, addition of thermal insulation is important, particularly in regions with extreme climates [4].

The employ of thermal insulation is one of the most effective ways of building energy conservation for cooling and heating. Therefore, the selection of a proper insulation material and determination of optimum insulation thickness are particularly vital [5]. It is well known that the heat-transmission load decreases without a limit with increasing insulation thickness, however, the rate of

* Tel.: +90 0424 2370000/5338.
E-mail address: mozel@firat.edu.tr

0196-8904/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2013.08.013

Nomenclature

a	solar absorptivity of outdoor surface of wall
A_s	annual energy savings ($/m^2 yr)
c	specific heat (J/kg K)
C_A	yearly total cost of energy ($/m^2 year)
C_i	cost of insulation material per unit volume ($/m^3)
C_F	fuel cost ($/kg)
C_t	total cost ($/m^2)
g	inflation rate
h_i	heat-transfer coefficient at the indoor surface of wall (W/m^2 K)
h_o	heat-transfer coefficient at the outdoor surface of wall (W/m^2 K)
H_u	lower heating value of the fuel (kJ/kg)
I_T	incident total solar radiation for vertical surfaces (W/m^2)
I_b	beam solar radiations on the horizontal surface (W/m^2)
I_d	diffuse solar radiations on the horizontal surface (W/m^2)
I	total solar radiations on the horizontal surface (W/m^2)
i	interest rate
k	thermal conductivity (W/m K)
L_i	insulation thickness (m)
M_F	yearly fuel consumption (kg/m^2 year)
N	lifetime (years)
p_b	payback period (years)
PWF	present worth factor
q_i	heat flux at indoor surface of the wall (W/m^2)
Q_l	total heat loss per year of insulated wall (kW h/m^2)
S_e	The energy savings ($/m^2)
t	time (s)
T_i	indoor air temperature (°C)
T_o	outdoor air temperature (°C)
$T_{x=L}$(max)	maximum of indoor surface temperature (°C)
$T_{x=L}$ (min)	minimum of indoor surface temperature (°C)
$T_{x=0}$ (max)	maximum of outdoor surface temperature (°C)
$T_{x=0}$ (min)	minimum of outdoor surface temperature (°C)
U	overall heat transfer coefficient of the wall (W/m^2 K)
Greek letters	
α	thermal diffusivity (m^2/s)
β	slope of the tilted surface
η_s	efficiency of the heating system
δ	declination angle (°)
ϕ	latitude (°)
Φ	time lag (h)
f	decrement factor
γ	surface azimuth angle (°)
ω	hour angle (°)
ρ	density (kg/m^3)
θ	incidence angle (°)
θ_z	zenith angle (°)

decrease drops quite fast as the thickness increases. From a purely conservation point of view, the designer should select an insulation material with the lowest possible thermal conductivity and the highest thickness that the owner can afford. However, the cost of insulation increases linearly with its thickness, and there is a point, for each type of insulation material, beyond which the saving in energy consumption will not compensate for the extra cost of insulation material. Thus, there must be an optimum insulation thickness at which the total cost of the insulation material plus the present worth of energy consumption over the lifetime of the building is a minimum [6].

In literature, studies dealing with the optimum insulation thickness are based on only heating loads [1,7–14], only cooling loads [15–18] and, both heating and cooling loads [2,5,6,19–29]. While most of those studies use degree-days (or degree-hours) concept which is a simple and crude model to estimate the transmission loads under static conditions [1,2,5,7–12,17–19], the others used dynamic transient models based on numerical and analytical methods to obtain highly accurate results [6,13–15,20–29].

In literature, although there are many studies on the determination of the optimum insulation thickness, these studies obtained by using dynamic models considering the transient thermal behavior of building envelope and solar radiation are in a limited number as mentioned above. The main objective of this study is to analyse as thermal, economical and environmental of the insulated building walls. The calculations are carried out under dynamic thermal conditions by considering different wall orientations for the climatic conditions of Kars located in a cold climate. Firstly, the thermal characteristics are calculated under steady periodic conditions. Secondly, the insulation thickness is optimized by using a cost analysis over lifetime of 20 years of the building. Lastly, fuel consumption and emissions of CO_2 and SO_2 are determined for different structure and insulation materials. Results are compared with corresponding results in under different climatic conditions.

2. Mathematical formulation and calculation procedure

A composite structure with M layers is shown schematically in Fig. 1. The outside surface is exposed to periodic solar radiation and outdoor environmental temperature while the inside surface is exposed to room air maintained at constant indoor design temperature.

Assuming no heat generation, constant thermal properties, one-dimensional heat transfer and negligible interface resistance, time-dependent heat conduction equation in a multi layer wall may be written as [20]:

$$\frac{\partial^2 T_j}{\partial x^2} = \frac{1}{\alpha_j}\frac{\partial T_j}{\partial t} \tag{1}$$

where $\alpha(= k/(\rho c))$ is the thermal diffusivity and the subscript j is layer number (j = 1,2,..., M), ρ, c and k are the density, the specific heat and the thermal conductivity, respectively.

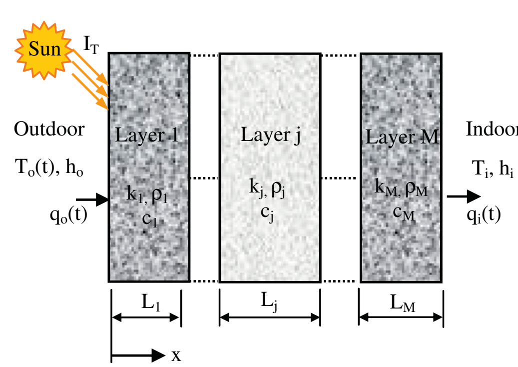

Fig. 1. M-layered composite wall.