DETERMINATION OF OPTIMUM THERMAL INSULATION THICKNESSES CONSIDERING THE SEASONAL ENERGY REQUIREMENTS

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Abstract— In this study, an optimization of the thermal insulation thickness applied to the external walls of buildings has been carried out based on the heating and cooling and the annual energy requirements considering solar radiation effect. This study has been performed for Istanbul, Turkey. Istanbul is located in the second climatic region in Turkey with *HDD*=1372, *CDD*=524. By determining the sol-air temperatures considering air temperatures and solar radiation vales for Istanbul and maximizing the annual energy savings, the optimum thermal insulation thicknesses have been calculated. The effects of solar radiation on heating-cooling energy requirements, the variation of optimum insulation thicknesses with degree-days, the differences between the analyses based on seasonal and annual have been presented in tabular and graphical form.

Keywords— Insulation thickness; space heating-cooling; sol-air temperature.

I. INTRODUCTION

In many countries, the energy requirements for space heating and cooling in buildings (both housing sector and commercial-industrial buildings) has the highest share of all which is about 50% of total energy consumed in buildings (Ozkahraman and Bolatturk 2006). For that reason, great amount of savings from heating or cooling energy requirements is possible by applying thermal insulation to buildings.

The optimum thermal insulation thickness depends on the cost of insulation material, building lifetime, coefficient of performance of the cooling equipment, efficiency of the heating system, the cost of energy source, and prevailing inflation and interest rates, in addition to these, it primarily depends on the heating and cooling loads of the buildings. For that reason, these loads should be determined accurately. The heat load from solar radiation has a significant effect on the heating and cooling loads of a building. In most studies, however, the solar radiation on building walls was not considered in the calculations of optimum insulation thickness.

In the literature, there are many studies dealing with optimum insulation thickness for buildings (Bolatturk 2006; Aytac and Aksoy 2006; Comakli and Yuksel 2003; Sisman et al 2007;Ucar and Balo 2010; Hasan 1999), or refrigeration applications (Soylemez and Unsal 1999; Usta and Ileri 1999). Aytac and Aksoy (2006) and Bolatturk (2006) calculated the optimum insulation thicknesses for different *DD* zones in Turkey considering heating energy requirement of buildings. However, the effect on the cooling energy requirement on the insulation thicknesses and the solar radiation were not investigated in these studies. ***both the heating and cooling loads were not considered together in the calculation of optimum insulation thickness, and the effect of solar radiation on these loads were not investigated.

In this study, taking into consideration the space-heating and cooling loads together, the optimum insulation thicknesses were calculated for Istanbul. Instead of air temperature, the solar-air temperature which considers the incident solar radiation on a wall was used in the calculation of heating and cooling transmission loads. The annual heating and cooling *DD*s were calculated using recent (about 5 year-measurements) outside air temperatures for each considered city.

II. MATHEMATICAL MODEL

Degree-days and solar radiation

Degree-days method assumes that the energy needs for a building are proportional to the difference between the daily mean outdoor temperature and the base temperature. Considering the solar heat gain through the external walls of a building, the annual heating and cooling degree-days (*HDD*and *CDD*) can be expressed as follows (Bolatturk 2008)

$$HDD = \sum_{1}^{365} \left(T_b - T_{sol-air}\right)^+ \quad (1)$$

$$CDD = \sum_{1}^{365} \left(T_{sol-air} - T_b\right)^+ \quad (2)$$

As seen above eqs. (1) and (2), the *HDD* and *CDD* values are dependent on the sol-air temperature. The sol-air temperature is a concept relating to the outside air temperature and the solar radiative flux, and defined as (Cengel 1998)

$$T_{sol-air} = T_o + \frac{\alpha_s \dot{q}_s}{h_o} - \frac{\varepsilon\sigma\left(T_o^{\,4} - T_{surr}^{\,4}\right)}{h_o} \quad (3)$$

Being conservative, the solar absorptivities (α_s) of light- and dark-colored surfaces are taken 0.45 and 0.90, respectively. Recommended summer and winter design values for heat transfer coefficients on outer surfaces of a building are h_o = 22.7 W/m^{2}K and h_o = 34.0 W/m^{2}K respectively.

The solar radiation incident on a surface depends on surface gradient (slope) and orientation. Firstly, the daily solar radiation on a horizontal surface is determined, which is given by

$$\frac{\dot{q}_h}{\dot{q}_{o,h}} = \left(a + b\frac{S}{S_0} \right) \quad (4)$$

The coefficients a and b are a function of solar declination angle (δ) and latitude of the site (ϕ) and altitude (Z) (Kilic and Ozturk, 1983)

The monthly average daily extraterrestrial radiation on per unit of horizontal surface can be computed as follows

$$\dot{q}_{o,h} = \frac{G_{sc}}{\pi}\left[1 + 0.033\cos\left(n\frac{360}{365}\right)\right]\left[\cos\phi\cos\delta\sin\omega_s + \frac{\pi}{180}\omega_s\sin\phi\sin\delta\right] \quad (5)$$

whereG_{sc} is the solar constant, ω_s is the sunset hour angle for the month, and n is the day of the year. The solar constant is given as 1367 W/m^2 (Sukhatme 1999). The declination angle and the sunset hour angle are determined as (Duffie and Beckman 1991)

$$\delta = 23.45\sin\left(\frac{360}{365}(284 + n)\right) \quad (6)$$

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \quad (7)$$

In addition the surface slope, its orientation has a significant effect on the falling solar radiation. The orientation of the surface is expressed with the surface azimuth angle (γ). R_b is the ratio of the daily direct radiations for sloping and horizontal surfaces, and it also varies according to surface azimuth angle. R_b, for example for a surface facing south, is given by

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\sin\omega_s' + \pi/180\omega_s'\sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_s + \pi/180\omega_s\sin\phi\sin\delta} \quad (8)$$

Incoming solar energy on vertical surfaces such as walls can be calculated from the following equation.

$$\dot{q}_s = \dot{q}_h\left(1 - \frac{\dot{q}_{h,d}}{\dot{q}_h}\right)R_b + \dot{q}_{h,d}\left(1 + \frac{\cos\beta}{2}\right) + \dot{q}_h\rho\left(1 - \frac{\cos\beta}{2}\right) \quad (9)$$

whereβ is the surface inclination angle and β = 90° for vertical surfaces, ρ is the ground reflectance, which is conservatively assumed to be 0.2.

Annual heating and cooling energy requirements

The structure and properties of external wall considered in this study are given in Table 1.Heat loss and gain through a unit area of the wall are respectively,

$$q = U(T_b - T_{sol-air}) \quad (10)$$

$$q = U(T_{sol-air} - T_b) \quad (11)$$

In terms of degree-days, the annual heating and cooling energy requirements per unit area because of the heat loss from the wall can be expressed as follows

$$q_{A,H} = 86400\, HDD\, U/\eta \quad (12)$$

$$q_{A,C} = 86400\, CDD\, U/COP \quad (13)$$

whereCOP is the coefficient of performance of the cooling system. COP depends on the operating parameters, but on the average, it is assumed to be 2.5 (Soylemez and Unsal 1999; Bolatturk 2008).

The overall heat transfer coefficient of a typical external wall that includes a layer of insulation is given by

$$U = \frac{1}{1/h_i + R_w + x/k + 1/h_o} = \frac{1}{R_{t,w} + x/k} \quad (14)$$

Table 1. The parameters used in the calculations

Parameter		Value
Wall structure		
3 cm	external plaster	k = 0.87 W/mK
x cm	Insulation material	k = 0.030 W/mK
20 cm	hollow brick	k = 0.45 W/mK
2 cm	internal plaster	k = 0.87 W/mK
	inside heat transfer coefficient	h_i = 8.29 W/m^{2}K
	outside heat transfer coefficient	h_o = 34.0 W/m^{2}K
		U=1/(R_{ins}+0.652) W/m^{2}K
Insulation (polystyrene)		
density		ρ> 30 kg/m^3
conductivity		k = 0.030 W/mK
material cost		C_{ins} = 90 USD/m^3
Natural gas (in heating)		
Price, C_f		0.367 USD/m^3
Lower heating value, Hu		34.526 x 10^6 J/m^3
Efficiency of heating system, η		0.93
Electricity (in cooling)		
Price, C_e		0.118 USD/kWh
COP		2.5

Energy costs and optimum insulation thickness

In this study, the life cycle cost (LCC) analysis is used in the energy cost calculations. LCC analysis calculates the total cost of heating/cooling over the lifetime (*LT* in years). Assuming an inflation rate (*i*), an interest rate (*g*) and an expected lifetime, the present worth factor (*PWF*) is calculated as (Al-Sanea et al 2003)

$$PWF = \left(\frac{1+i}{g-i}\right)\left[1-\left(\frac{1+i}{1+g}\right)^{LT}\right] \quad (15)$$

The annual total (heating and cooling) cost and the optimum insulation thickness are given by

$$C_{t,A} = C_{ins}x + \frac{86400HDD\,C_f\,PWF}{(R_{t,w}+x/k)Hu\eta} + \frac{86400CDD\,C_e PWF}{(R_{t,w}+x/k)COP} \quad (16)$$

$$x_{opt,A} = \left(\frac{86400PWF\left(C_f HDD/\eta\,Hu + C_e CDD/COP\right)k}{C_{ins}}\right)^{1/2} - R_{t,w}k \quad (17)$$

Insulation used on external wall decreases not only the heating cost but also the cooling cost. For that reason, from an economic point of view, both the heating and cooling energy requirements should be considered together when calculating the optimum insulation thickness.

III. RESULTS AND DISCUSSION

The *HDD* (T_b=18°C) and *CDD* (T_b=24°C) values considering and not considering solar load for Istanbul are given in Table 2. When calculating the first values (i.e. with asterisk) for degree-days in this table, the solar load is not considered. When the heat load caused by solar radiation on the surface is added in the calculations (i.e. without asterisk), the heating load in winter season is obtained smaller and the cooling load in summer season is obtained greater (*HDD*<*HDD** and *CDD*>*CDD**). Table 2 clearly indicates that the solar radiation has a significant effect on both the heating and cooling loads.

Table 2. The *HDD* and *CDD* values

Zone	City	*HDD**	*HDD*	*CDD**	*CDD*
II	Istanbul	1908.0	1371.5	145.6	523.6

* The degree days were calculated without taking into account of sol-air temperature

The variation of heating and cooling degree-days with months is shown in Fig. 1 for the base temperatures of 18ºC and 24ºC respectively.

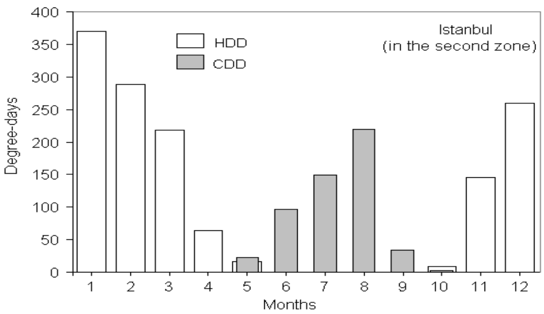

Fig. 1. Variation of monthly degree-days

The effect of insulation thickness on the annual heating and cooling energy requirements per square meter of wall is shown in Fig. 2(a). The variation of cost curves with insulation thickness, and the determination of optimum insulation thicknesses according to different approaches (heating total cost, cooling total cost or annual total cost) is shown in Fig. 2(b). The insulation thickness minimizing the total cost is taken as the optimum insulation thickness). Adding more insulation decreases both the heating and cooling transmission loads (heating and cooling costs) together. As a consequence of this, the effect of the insulation cost in the annual total cost decreases. This decrease causes thicker insulation thickness. Therefore, $x_{opt,A}>x_{opt,H}$ or $x_{opt,A}>x_{opt,C}$ are obtained.

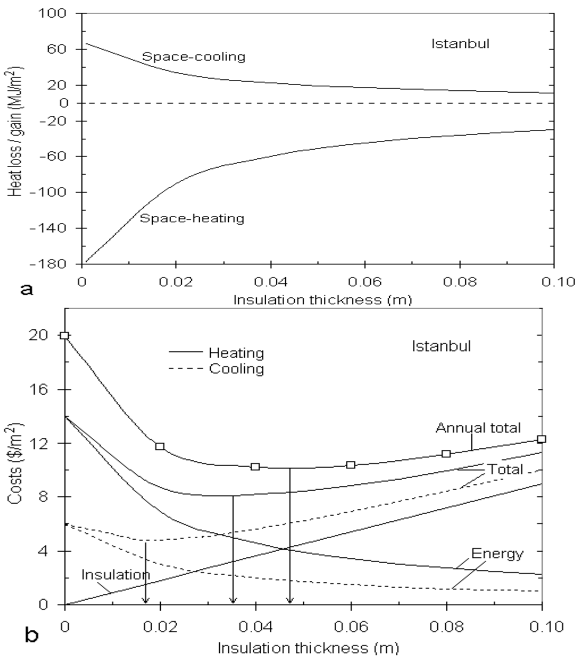

Fig. 2 (a) Annual heating or cooling transmission loads and (b) heating and cooling costs variations with insulation thickness

In general, the variation of optimum insulation thicknesses with degree-days is shown in Fig. 3. The optimum insulation thicknesses increases (but not linearly) with increasing *DD* values because of the fact that high *DD* value means the high energy requirement (heating or cooling). It is also seen in this figure that $x_{opt,A}$ is greater than $x_{opt,H}$ and $x_{opt,C}$ as mentioned above. On the other hand, $x_{opt,C}$ is higher than $x_{opt,H}$ for the same degree-day value. The reason of this is the unit cost of energy. For heating, the unit cost of energy is $C_f/(Hu.\eta)$ in USD/J, for cooling it is C_e/COP in USD/kWh.

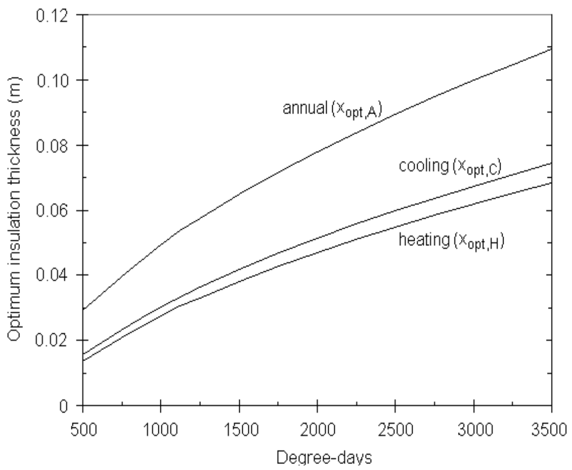

Fig. 3. Variation of optimum insulation thicknesses with degree-days

CONCLUSION

In this study, the optimum thermal insulation thicknesses on external walls of buildings were calculated based on both annual and seasonal energy loads. The effect of cases considering and not considering the incident solar radiation on seasonal heating/cooling loads were investigated. The results show that solar radiation greatly affects the heating and cooling loads. The insulation thickness calculations should be carried out on the basis of annual energy requirement instead of only seasonal. Moreover, by using the optimum insulation thickness, the annual energy savings reaches up to 48%.Since the energy unit cost for cooling is greater than that for heating, the $x_{opt,C}$ is obtained higher than $x_{opt,H}$ for the same degree-day value.

Nomenclature

C cost, USD m^{-2}
CDD cooling degree-days, °C
CDD^* cooling degree-days considering solar radiation, °C
COP coefficient of performance of the cooling system
g interest rate
G_{sc} solar constant, W/m^2
h_o combined convection and radiation heat transfer coefficient, $Wm^{-2}K^{-1}$
HDD heating degree-days, °C
HDD^* heating degree-days considering solar radiation, °C
Hu lower heating value of fuel, Jm^{-3}
i inflation rate
k thermal conductivity of insulation material, $Wm^{-1}K^{-1}$
K_T clearness index
LT expected lifetime, year
n day of year
PWF the present worth factor
q energy requirements per unit area, Jm^{-2}
$\dot{q}$ mean daily solar radiation on per unit area of a surface, Wm^{-2}
$\dot{q}_s$ mean daily solar radiation on per unit area of a sloped (vertical) surface, Wm^{-2}
R thermal resistance of external wall, m^2KW^{-1}
R_b ratio of the daily direct radiations for sloping and horizontal surfaces
S day length
S_0 maximum possible sunshine duration
T temperature, °C
U overall heat transfer coefficient, $Wm^{-2}K^{-1}$
x insulation thickness, m
Z altitude, m

Greek symbols

α_s solar absorptivity of surface
β surface inclination angle
γ surface azimuth angle
δ solar declination angle
ε emissivity of surface
η efficiency of the heating system
ϕ latitude of the site
ρ ground reflectance
σ Stefan-Boltzman constant
ω_s sunset hour angle for the month
ω_s' sunset hour angle for inclined surface

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