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DETERMINATION OF OPTIMUM THERMAL INSULATION THICKNESSES FOR EXTERNAL WALLS CONSIDERING THE HEATING, COOLING AND ANNUAL ENERGY REQUIREMENTS

Ömer KAYNAKLI *

Faruk KAYNAKLI **

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Abstract: In this study, optimization of thermal insulation thickness applied to the external walls of buildings has been carried out comparatively based on the seasonal (space-heating and cooling) and the annual energy requirements considering solar radiation effect. This study has been performed for four degree-day regions of Turkey, namely, Iskenderun (in the first region), Istanbul (in the second region), Ankara (in the third region) and Ardahan (in the fourth region). By determining the sol-air temperatures for each region and maximizing the present worth value of seasonal and 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 and payback periods with respect to degree-day regions, 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

Isıtma, Soğutma ve Yıllık Enerji İhtiyaçları Dikkate Alınarak Dış Duvarlar için Optimum Yalıtım Kalınlıklarının Belirlenmesi

Öz: Bu çalışmada dış duvarlara uygulanan yalıtım kalınlığının optimizasyonu, güneş radyasyonu etkisiyle birlikte hacimsel ısıtma, soğutma ve yıllık enerji gereksinimleri dikkate alınarak yapılmıştır. Bu çalışma, Türkiye'deki 4 derece-gün bölgesinde yer alan iller için yürütülmüştür: İskenderun (1. bölgede), İstanbul (2. bölgede), Ankara (3. bölgede) ve Ardahan (4. bölgede). Her bölge için güneş-hava sıcaklıkları belirlenerek sezonluk ve yıllık enerji tasarrufunu maksimize ederek optimum yalıtım kalınlıkları hesaplanmıştır. Güneş radyasyonunun ısıtma-soğutma enerji yüklerine etkisi, derece-gün bölgelerine göre optimum yalıtım kalınlıklarının ve geri ödeme sürelerinin değişimi, sezonluk ve yıllık analizler arasındaki farklar tablolar ve şekiller yardımıyla sunulmuştur.

Anahtar Kelimeler: Yalıtım kalınlığı, hacimsel ısıtma-soğutma, güneş-hava sıcaklığı

1. 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, Kalfa and Yaşar 2015). For that reason, great amount of savings from heating or cooling energy requirements is

* Uludag University Faculty of Engineering, Mechanical Engineering Department Görükle, 16059 Bursa

** Uludag University, Gemlik Asım Kocabıyık MYO Department

Corresponding Author: Ömer.Kaynaklı (kaynakli@uludag.edu.tr)

possible by applying thermal insulation to buildings. Insulation reduces not only the energy requirements for heating and cooling but also its polluting products such as CO_2, CO, SO_2 and the dust particles (Dombayci 2007; Comakli and Yuksel 2004). Furthermore, insulation also improves interior thermal comfort conditions by minimizing heat losses/gains from/to buildings in winter and summer seasons, respectively. On the other hand, amount of insulation material to be used is an important factor. Although heat loss and gain decrease with increasing thickness of insulation, the total cost of insulation (material and installation costs) also increases. For that reason, the most appropriate insulation thickness should be determined with respect to the costs.

Turkey, in general, is a country that has severe cold and hot climate conditions. According to the regulation TS 825 (TS825 1999), Turkey is divided into four heating degree-day regions in which the fourth region has the most severe winter condition, so a large amount of energy is used to the heat buildings. When all degree-day (*DD*) regions in Turkey are considered, recent studies reveal that technical potential savings in residential buildings ranges from 25% to 45% (Kaygusuz and Kaygusuz 2002).

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. Comakli and Yuksel (2003) determined the optimum insulation thicknesses for only three cities located in fourth region in Turkey. They found that the optimum insulation thicknesses for each city are 10.4, 10.7 and 8.5 cm respectively when coal is used for heating. Sisman et al. (2007) investigated the optimum insulation thicknesses for external wall and roof (ceiling) with respect to different *DD* regions, but they focused on only four cities in Turkey. Similarly, a more recent study was carried out by Ucar and Balo (2010) to optimise the insulation thickness only for certain cities in Turkey on the basis of *HDD*s and *CDD*s. Soylemez and Unsal (1999) and Usta and Ileri (1999) stated on the optimum insulation thickness for only refrigeration applications with vapor compression. Another study was carried out by Bolatturk (2008) to investigate the optimum insulation thicknesses and payback periods for seven cities located in the warmest zone in Turkey on the basis of heating and cooling degree-hour values of these cities. He emphasised that the optimisation of the insulation thickness with respect to the cooling load is more appropriate for warm regions because the thicknesses of the insulation material (polystyrene) varied between 3.2 and 3.8 cm for cooling degree-hours and between 1.6 and 2.7 cm for heating degree-hours. Kaynakli (2008) investigated the residential heating energy requirements and optimum insulation thickness on a prototype building in Bursa, Turkey. The variation of the annual heating energy requirement of the building for various architectural design properties and the optimum insulation thicknesses for different fuel types were investigated. As a consequence, it was found that the optimum insulation thicknesses for Bursa vary between 5.3 and 12.4 cm depending on the fuel type used for heating. Buyukalaca et al. (2001) presented only the distribution of heating and cooling degree-day (*HDD* and *CDD*) values in Turkey, which does not consider the incident solar radiation. Dombayci (2007) investigated the environmental impact of thermal insulation for the case of Denizli, Turkey. In the calculations, coal was used as the fuel source and expanded polystyrene was the insulation material. He determined that CO_2 and SO_2 emissions were cut by 42% when the optimum insulation thickness was used in the external walls of buildings. In a more recent study, by using the *HDD* values Ucar (2010) obtained the optimum insulation thicknesses as 0.038 m, 0.046 m, 0.057 m, and 0.074 m for four cities in Turkey, namely Antalya, Istanbul, Elazig, and Erzurum respectively. Moreover, it was found that by using the optimum insulation thickness in buildings for Erzurum, the CO_2 and SO_2 emission rates of fuel would be reduced by 79%. As can be seen from above-mentioned 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. Additionally, prevailing outside air temperature records were not used in the heating and cooling *DD*s calculations.

In this study, apart from the above mentioned studies, taking into consideration the space-heating and cooling loads together, the optimum insulation thicknesses were calculated for each *DD* region in Turkey. 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.

2. MATHEMATICAL MODEL

2.1. Degree-days and Solar Radiation

Degree-days method is one of the simplest and most intuitive ways of estimating the annual energy consumption of a building. The method assumes that the energy needs for a building are proportional to the difference between the daily mean outdoor temperature and the base temperature. The base temperature is the outdoor temperature above or below which cooling or heating is needed. Considering the solar heat gain through the external walls of a building, the annual heating degree-days (*HDD*) can be expressed as follows (Bolatturk 2008)

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

where T_b is the base temperature and $T_{sol\text{-}air}$ is the solar air (sol-air) temperature. The plus sign above the parenthesis indicates that only positive values are to be counted, and hence the temperature difference is to be taken to be zero when $T_{sol\text{-}air} > T_b$. Also, the number of annual cooling degree-days (*CDD*) is defined as follows

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

where the temperature difference is to be taken to be zero when $T_b > T_{sol\text{-}air}$. As seen above eqs. (1) and (2), the *HDD* and *CDD* values are dependent on the sol-air temperature. For opaque surfaces such as the walls and the roof, the effect of solar radiation is conveniently accounted for by considering the outside temperature to be higher by an amount equivalent to the effect of solar radiation. This is done by replacing the ambient temperature in the heat transfer relation through the walls and the roof by 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)

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

where T_o is the outside air temperature, α_s the solar absorptivity of the surface, h_o is the outer surface combined convection and radiation heat transfer coefficient, $\dot{q}_s$ is the solar radiation incident on the surface, ε is the emissivity of the surface, σ is the Stefan-Boltzman constant, and T_{surr} is sky and surrounding surface temperature. In this equation, the second term indicates the solar heat gain effect on the opaque surface while the last term represents the correction to the radiation heat transfer between surface and environment if T_{surr} is different from T_o. In practice, the radiation correction effect varies from 0°C for vertical surfaces to 3.9°C for horizontal or upward-facing surfaces (the sky overhead is colder than the rest of environment). Being conservative, the solar absorptivities 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 on per unit of horizontal surface (in kJ/m^2.day) for each city in Turkey was presented in Turkish Standard 3817 (TS3817 1994). The solar radiation incident on a surface depends on surface gradient (slope) and orientation. The solar radiation for the vertical surfaces such as outside walls of buildings can be found as follows: Firstly, the daily solar radiation on a horizontal surface is determined, which is given by

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

where $\dot{q}_h$ is the monthly average daily global solar radiation, $\dot{q}_{o,h}$ is the monthly average daily extraterrestrial radiation, S the day length, S_0 the maximum possible sunshine duration, a and b are empirical coefficients relating with the region. Moreover, $\dot{q}_h / \dot{q}_{o,h}$ is also expressed as the clearness index (K_T). Kilic and Ozturk (1983) determined for Turkey that the coefficients a and b are a function of solar declination angle (δ) and latitude of the site (ϕ) and altitude (Z), as given by the equations

$$a = 0.103 + 0.000017\, Z + 0.198\cos(\phi - \delta) \tag{5}$$

$$b = 0.533 - 0.165\cos(\phi - \delta) \tag{6}$$

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

$$\dot{q}_{o,h} = \frac{G_{sc}}{\pi}\left[1 + 0.033\cos\left(n\frac{360}{365}\right)\right]\left[\cos\phi\cos\delta\sin\omega_s + \frac{\pi}{180}\omega_s\sin\phi\sin\delta\right] \tag{7}$$

where G_{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)

$$\delta = 23.45\sin\left(\frac{360}{365}(284 + n)\right) \tag{8}$$

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \tag{9}$$

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). The surface azimuth angle attains 270° (east), 90° (west), 180° (north) and 0° (south). 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

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\sin\omega_s' + \pi/180\omega_s'\sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_s + \pi/180\omega_s\sin\phi\sin\delta} \tag{10}$$

where ω_s' is the sunset hour angle for inclined surface, which is given following equation where the minimum value is stored.

$$\omega_s{}' = \min\begin{bmatrix}\cos^{-1}(-\tan\phi\tan\delta)\\ \cos^{-1}(-\tan(\phi-\beta)\tan\delta)\end{bmatrix} \tag{11}$$

The equation of mean daily diffuse solar radiation on a horizontal surface ($\dot{q}_{h,d}$), which is based on approximately 10-year measurements, is developed by Tiris et al. (1995), as follows

$$\dot{q}_{h,d} = \dot{q}_h\left(0.703 - 0.414K_T - 0.428K_T{}^2\right) \tag{12}$$

where K_T is the clearness index as mentioned above. Hence, incoming solar energy on vertical surfaces such as walls can be calculated from the following equation.

$$\dot{q}_s = \dot{q}_h\left(1-\frac{\dot{q}_{h,d}}{\dot{q}_h}\right)R_b + \dot{q}_{h,d}\left(1+\frac{\cos\beta}{2}\right) + \dot{q}_h\rho\left(1-\frac{\cos\beta}{2}\right) \tag{13}$$

where β is the surface inclination angle and β = 90° for vertical surfaces, ρ is the ground reflectance, which is conservatively assumed to be 0.2 (CIBSE 1982).

In Turkey, to improve the energy conservation in buildings, a regulation was issued in 1999 about building insulation (TS825 1999). According to the regulation, four different *DD* regions have been defined for Turkey. There are significant differences among the heating and cooling *DD*s depending on different regions. The difference among the heating *DD*s in different regions increases up to approximately 7 times at a base temperature of 18°C (Buyukalaca et al 2001). In this study, as an example, a city was chosen in each degree-day region as follows: Iskenderun/Hatay, Istanbul, Ankara, and Ardahan. The degree-day region and certain features of these cities are given in Table 1.

Table 1. The certain data for selected cities in each degree-day zone

City	Degree-day zone	Longitude	Latitude	Altitude (m)	Winter outdoor design temp. (°C)	Summer outdoor design temp. (°C)
Hatay/Iskenderun	I	36.07	36.37	3	3	37
Istanbul	II	29.05	40.58	39	-3	33
Ankara	III	32.53	39.57	894	-12	35
Ardahan	IV	42.42	41.08	1829	-21	30

2.2. Annual Heating and Cooling Energy Requirements

The structure of external wall considered in this study consists of 2 cm inner plaster (k=0.87 W/mK), 20 cm horizontal hollow brick (k=0.45 W/mK), 3 cm external plaster (k=0.87 W/mK) and insulation material (k=0.035 W/mK). Heat loss or gain through a unit area of the wall, the properties of which are given in Table 2, is respectively

Table 2. 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 (for winter)
		h_o = 22.7 W/m^{2}K (for summer)
		U =1/(R_{ins}+0.652) W/m^{2}K (for winter)
		U =1/(R_{ins}+0.667) W/m^{2}K (for summer)
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
Financial parameters		
inflation rate, i		9%
interest rate, g		17%
lifetime, LT		10
present worth factor, PWF		6.91 (with eq. 21)

$$q = U\left(T_b - T_{sol-air}\right) \tag{14}$$

$$q = U\left(T_{sol-air} - T_b\right) \tag{15}$$

where U is the overall heat transfer coefficient. In terms of degree-days, the annual heating energy requirement per unit area because of the heat loss from the wall can be expressed as follows

$$q_{A,H} = 86400\ HDD\, U / \eta \tag{16}$$

where η is the efficiency of the heating system, which is assumed to be 0.93 for a typical heating system using natural gas (Bolatturk 2006). Because of the heat gains, the annual cooling energy requirement per unit area can be written as

$$q_{A,C} = 86400\ CDD\, U / COP \tag{17}$$

where *COP* 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

$$U = \frac{1}{1/h_i + R_w + x/k + 1/h_o} \tag{18}$$

where h_i and h_o are the inside and outside heat transfer coefficients respectively, R_w is the total thermal resistance of the composite wall materials without insulation, x and k are the thickness and thermal conductivity of insulation material, respectively. The heat transfer coefficient on the inner surfaces of a building is commonly used as h_i = 8.29 W/m^{2}K. On the other hand, the heat transfer coefficient on the outer surfaces was mentioned above for summer and winter conditions. The total wall thermal resistances excluding the insulation layer ($R_{t,w}$) are calculated as 0.667 m^{2}K/W and 0.652 m^{2}K/W for summer and winter conditions respectively (see Table 2). And thus, U can be rewritten as follows

$$U = \frac{1}{R_{t,w} + x/k} \tag{19}$$

2.3. Energy Costs and Optimum Insulation Thickness

It is obvious that as the thickness of insulation increases, the cost of insulation applied increases, but on the other hand, the heating/cooling load and their energy costs decrease. Adding more insulation increases the total cost of material used in proportion to its thickness. The cost of the extra thickness of insulation should then be balanced against the reduced costs of heating/cooling energy. The optimum insulation thickness is the thickness at which the total cost (i.e. energy and insulation costs) is a minimum. Choosing an insulation thickness value apart from the optimum one increases the total cost.

The cost of insulation used on external wall is a function of its thickness, which is given by

$$C_{t,ins} = C_{ins} x \tag{20}$$

where C_{ins} is the cost of insulation material per unit volume. The total cost is the sum of the cost of insulation plus the present value of the cost of heating/cooling energy over the lifetime of the building. 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), which is extensively discussed in Bolatturk (2006), Mearig et al (1999), Al-Sanea et al (2005) and Al-Sanea et al (2003).

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)

In case $g \neq i$,

$$PWF = \left(\frac{1+i}{g-i}\right)\left[1-\left(\frac{1+i}{1+g}\right)^{LT}\right] \tag{21}$$

In case $g = i$,

$$PWF = \frac{LT}{1+g} \tag{22}$$

LT is assumed to be 10 years (Bolatturk 2006; Hasan 1999). Thus, the total cost for heating can be expressed as follows

$$C_{t,H} = C_{ins}x + \frac{86400 HDD\, C_f\, PWF}{(R_{t,w} + x/k) Hu \eta} \tag{23}$$

where *Hu* is lower heating value of the fuel, C_f is the cost of fuel. In this study, natural gas is chosen as fuel in heating because of the fact that its usage for space heating has continued to expand in recent years in Turkey. The certain values related to natural gas are also given in Table 2 (Aytac and Aksoy 2006).

The optimum insulation thickness for heating season is obtained by minimizing eq. (23). The derivative of $C_{t,H}$ equation with respect to insulation thickness is taken and set equal to zero from which the optimum insulation thickness ($x_{opt,H}$) for heating degree-day is obtained as

$$x_{opt,H} = \left(\frac{86400\, HDD\, C_f\; PWF\, k}{\eta\, Hu\, C_{ins}} \right)^{1/2} - R_{t,w}k \tag{24}$$

Similarly, the total cost and the optimum insulation thickness for cooling season can be expressed as follow

$$C_{t,C} = C_{ins}x + \frac{86400 CDD\, C_e PWF}{(R_{t,w} + x/k) COP} \tag{25}$$

$$x_{opt,C} = \left(\frac{86400\, CDD\, C_e\; PWF\, k}{COP\, C_{ins}} \right)^{1/2} - R_{t,w}k \tag{26}$$

where C_e is the cost of electricity since the cooling system is supplied with electricity. The cost of electricity expressed as USD/kWh is given in Table 2.

Above equations are valid for only heating or cooling season respectively. So, $x_{opt,H}$ is the optimum insulation thickness for taking into account of only heating energy requirement. But, the annual total cost is the sum of the heating and cooling energy costs. Therefore, the annual total cost and the optimum insulation thickness considering the annual total cost are given by

$$C_{t,A} = C_{ins}x + \frac{86400 HDD\, C_f\, PWF}{(R_{t,w} + x/k) Hu \eta} + \frac{86400 CDD\, C_e PWF}{(R_{t,w} + x/k) COP} \tag{27}$$

$$x_{opt,A} = \left(\frac{86400 PWF\, (C_f\, HDD/\eta\, Hu + C_e CDD/COP) k}{C_{ins}} \right)^{1/2} - R_{t,w}k \tag{28}$$

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.

3. RESULTS AND DISCUSSION

The *HDD* (T_b=18°C) and *CDD* (T_b=24°C) values considering and not considering solar load for selected cities are given in Table 3. 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 3 clearly indicates that the solar radiation has a significant effect on both the heating and cooling loads. In addition to this, naturally *HDD* attains high values while *CDD* low values in cold climate regions such as fourth zone. For example, for Ardahan, the *CDD* is a small value as 22.4, which can be almost negligible.

Table 3. The *HDD* and *CDD* values

Zone	City	*HDD**	*HDD*	*CDD**	*CDD*
I	Hatay/Iskenderun	737.5	368.0	412.6	1047.6
II	Istanbul	1908.0	1371.5	145.6	523.6
III	Ankara	3158.6	2412.2	39.1	262.3
IV	Ardahan	4985.1	3974.2	0.2	22.4

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

During a year, the mean daily sol-air temperatures vary between -19.8 and 27.0ºC for Ardahan, vary between 6.7 and 34.2ºC for Iskenderun. The cooling load, as seen in Table 3, is relatively high for Iskenderun compared to other cities because of having more number of hot days in a year in addition to the high sol-air temperatures.

The variation of heating and cooling degree-days with months is shown in Fig. 1 for the base temperatures of 18ºC and 24ºC respectively. In this figure, the sol-air temperatures were taken into consideration in the calculations when determining the heating and cooling degree-days for each city. In relatively warmer regions (such as first and second zones), *CDD* is high while *HDD* is low. In relatively colder regions (such as third and fourth zones), the heating energy requirement (i.e. *HDD*) takes great values.

The effect of insulation thickness on the annual heating and cooling energy requirements per square meter of wall is shown in Fig. 2(a). As mentioned before, as the insulation thickness increases, both the heating and cooling loads decrease by diminishing increments. 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 heating and cooling energy costs decreases whereas the insulation cost increase linearly with increase in the thickness of insulation. On the other hand, both the seasonal (heating and cooling) total costs and the annual total cost decreases in the beginning, and then increases slowly due to the insulation material cost. The insulation thickness minimizing the total cost is taken as the optimum insulation thickness). As an example, for Istanbul, the optimum insulation thicknesses are obtained 1.7 cm for cooling, 3.6 cm for heating and 4.7 cm for both (annual energy requirement). The computed thicknesses for only heating or cooling season ($x_{opt,H}$ or $x_{opt,C}$) are thinner than that for the annual total energy loads ($x_{opt,A}$). 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.

When similar calculations are performed for other cities, the results given in Fig. 3 are obtained. It is seen that insulation is not required for Ardahan in cooling season ($x_{opt,C}$ =0 cm). Because, there is not an economic insulation thickness since the insulation does not pay back the its initial investment cost during lifetime (*LT*=10 years). On the other hand, for heating season the optimum insulation thickness is quite high as 7.5 cm because of high *HDD* value and energy cost in Turkey. It is also seen in the figure that in hot climate region (first region), since cooling load is higher than heating load, the cooling load is definitely taken into consideration in optimization of insulation thickness in building walls. If only the heating load is considered, the optimum insulation thicknesses vary in the range of 0.9 – 7.5 cm depending on cities. For only cooling load, it varies in the range of 0 – 3.2 cm. But, for annual energy requirements (heating + cooling), the optimum insulation thicknesses vary between 3.9 and 7.5 cm. It is noted that the sum of the $x_{opt,H}$ and $x_{opt,C}$ is not equal to $x_{opt,A}$ since the optimum insulation thickness does not vary linearly with *DD* values (or energy requirements) and the same energy source is not used in heating and cooling.

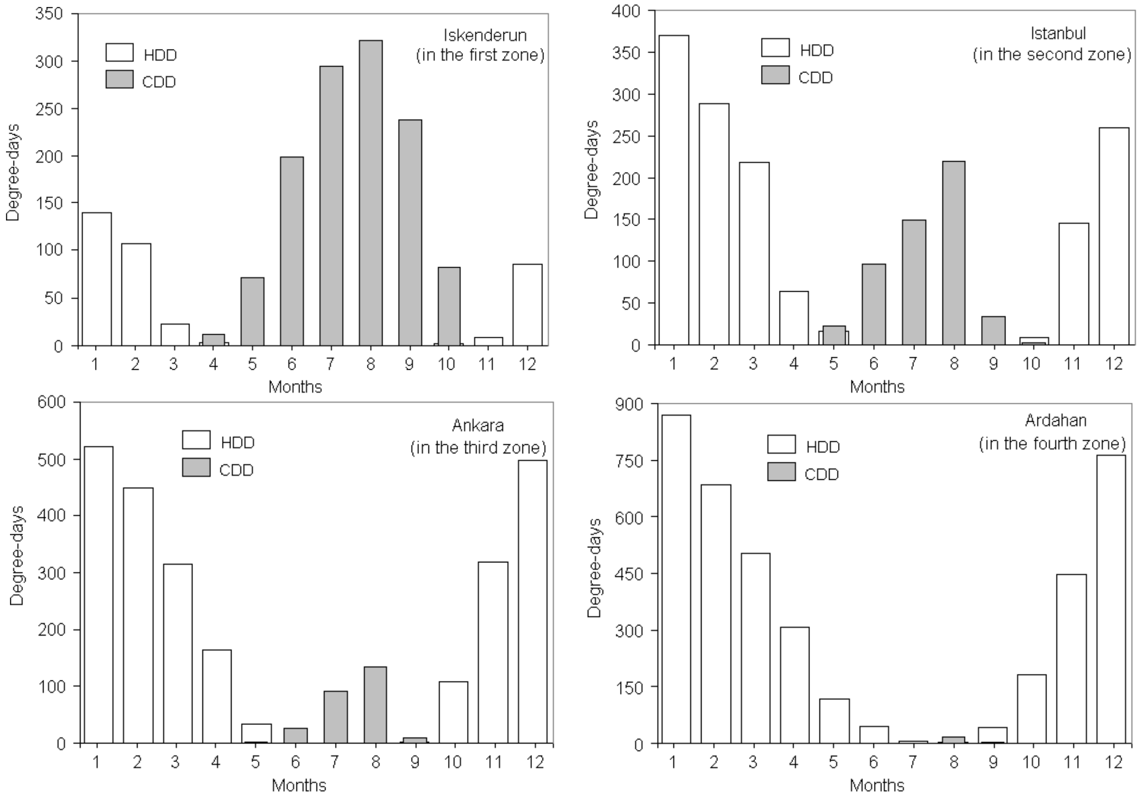

Figure 1:
Variation of monthly degree-days for considered cities

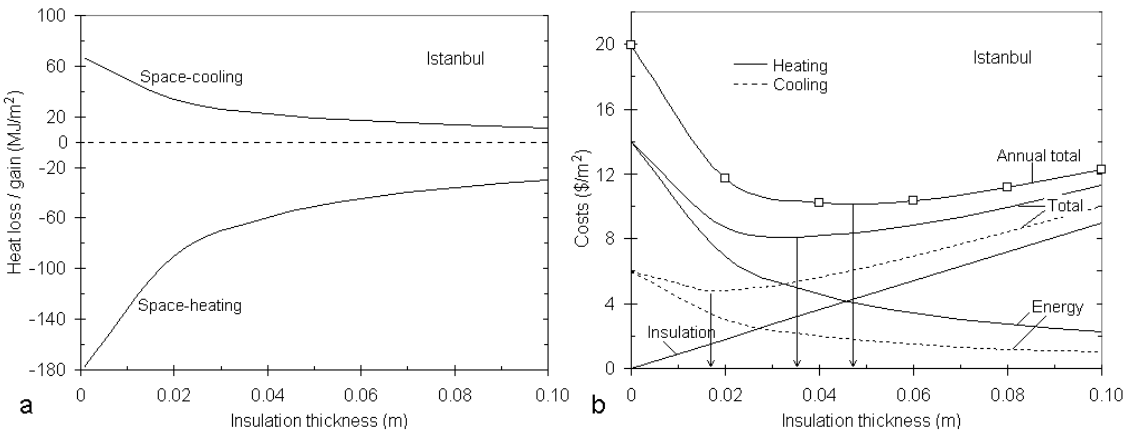

Figure 2:
(a) Annual heating or cooling transmission loads and (b) heating and cooling costs variations with insulation thickness

In general, the variation of optimum insulation thicknesses with degree-days is shown in Fig. 4. 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. In these unit costs, the performance of heating and cooling systems is taken into consideration besides the energy prices. Even though the heating and cooling degree-days are equal to each other, since the cooling-energy unit cost is higher than heating one, thicker insulation should be used in cold season for the same *DD* values for heating and cooling.

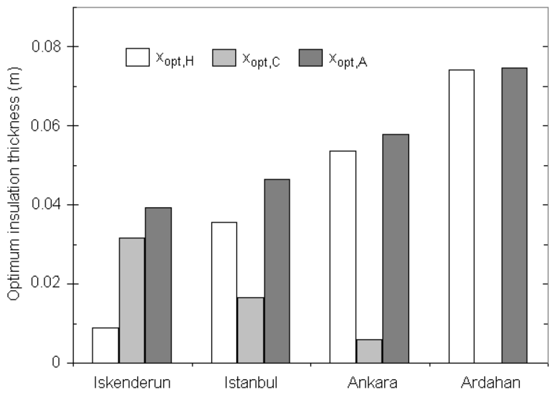

Figure 3:
The optimum insulation thicknesses considering heating, cooling and annual energy requirements

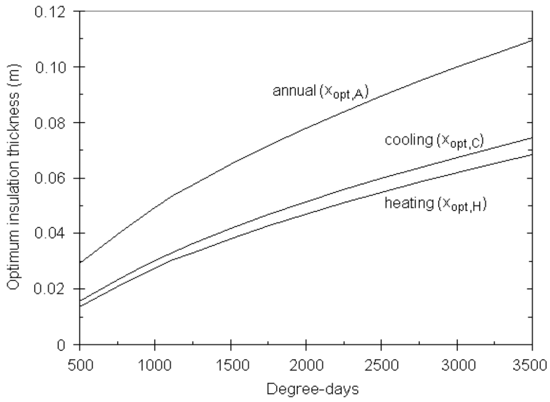

Figure 4:
Variation of optimum insulation thicknesses with degree-days

The amount of annual savings with insulation ($x_{opt,A}$) on external walls, for example Iskenderun, reaches up to approximately 45% as can be seen in Fig. 5. The optimum insulation thickness is also obtained from this figure. The insulation thickness at which the savings is maximum value gives the optimum insulation thickness. Choosing a thickness value apart from the optimum one will increase the total cost. The variation of savings for other cities can be seen in this figure as well. The maximum savings rate varies between 44 and 63% depending on cities. Since the annual total energy requirements (*HDD* + *CDD*) are higher for other cities, the savings rate gets higher values. So, the insulation is more significant for high annual total energy requirements instead of heating or cooling.

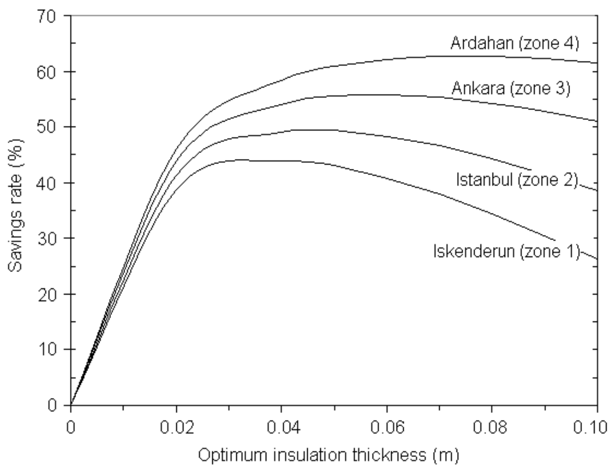

Figure 5:
Variation of energy savings with insulation thicknesses

The payback periods and the maximum amount of savings with the optimum insulation thickness are given in Fig. 6 for each city. The payback periods vary between about 1.5 and 2.2 years while the maximum amount of savings varies between about 45% and 65% depending on cities. Cities where the savings rate is high have short payback periods. Therefore, the application of insulation in such regions is more advantageous.

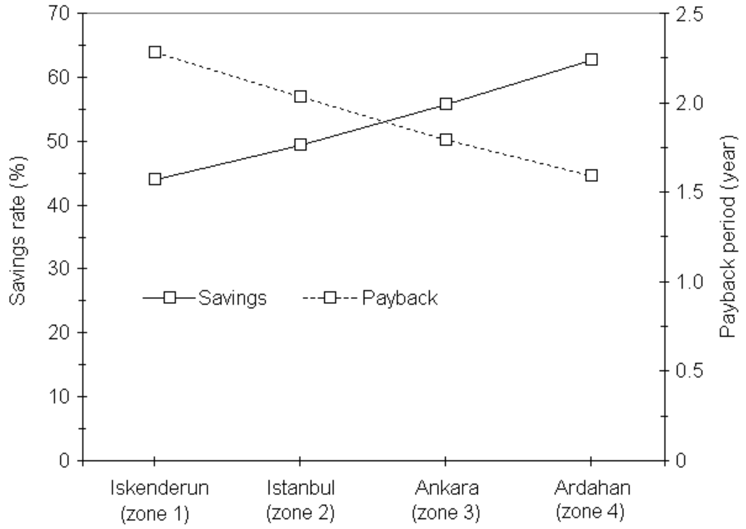

Figure 6:
Energy savings and payback periods for cities

4. 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 space heating-cooling loads were investigated. The results show that solar radiation greatly affects the heating and cooling loads. Especially in hot climate regions, incoming solar radiation on the walls decreases the heating load a little while it increases the cooling load more. The optimum insulation thicknesses considering annual energy requirements vary between 3.9 – 7.5 cm depending on cities. On the other hand, the optimum insulation thicknesses for only heating or cooling loads vary between 0.9 – 7.5 cm and 0 – 3.2 cm respectively. Therefore, the insulation thickness calculations should be carried out on the basis of annual (total) energy requirement instead of only seasonal, and thus, the advantages of insulation to be used on external walls can be seen more clearly. Moreover, by using the optimum insulation thickness, the annual energy savings varies between 44 and 63% depending on cities. The cities having high annual energy requirements for heating and cooling, the savings rates are high and because of this, the payback periods are short.

In addition to degree-days, energy unit costs for space-heating and cooling should also be considered. 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.

LIST OF SYMBOLS

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^{2}KW^{-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

Subscripts

A	annual
b	base
C	cooling
d	diffuse
e	electricity
f	fuel
h	horizontal
H	heating
ins	insulation
o	outside (*or* extraterrestrial for $\dot{q}$)
opt	optimum
sol-air	solar air
surr	sky and surrounding surface
t	total

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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