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OPTIMUM THERMAL INSULATION THICKNESSES AND PAYBACK PERIODS FOR BUILDING WALLS IN TURKEY

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Abstract: In this study, a procedure for optimizing the thermal insulation thickness for external walls has been presented and the optimum insulation thicknesses, energy savings and payback periods based on heating and cooling energy requirements have been calculated separately and also together for each city in Turkey. By considering the energy costs for heating and cooling, insulation material and installation costs, the optimum insulation thicknesses have been determined on the basis of life-cycle cost analysis over a building lifetime of 20 years. The results shows that the optimum thermal insulation thicknesses for only heating energy vary between 4.7 and 16.6 cm, vary between 0 and 3.8 cm for only cooling energy, and vary between 5.7 and 16.6 cm for total annual (heating + cooling) energy depending on the city. On the other hand, the payback periods in Turkey vary between 3.85 and 16.25 years when considering the total annual energy requirements. Furthermore, a parametric analysis has been also performed in order to investigate the effective parameters on the optimum insulation thickness and energy savings.
Keywords: Optimum thermal insulation thickness, Energy savings, Degree-days.

TÜRKİYE'DE BİNA DUVARLARI İÇİN OPTIMUM ISIL YALITIM KALINLIKLARI VE GERİ ÖDEME SÜRELERİ

Özet: Bu çalışmada, bina dış duvarlarında ısıl yalıtım kalınlığının optimizayonu için bir prosedür sunulmuş ve Türkiye'deki her şehir için ısıtma ve soğutma enerji gereksinimleri birlikte ve ayrı ayrı göz önüne alınarak optimum yalıtım kalınlıkları, tasarruf miktarları ve geri ödeme süreleri hesaplanmıştır. Hesaplamalarda ısıtma-soğutma enerji giderleri, yalıtım malzemesi ve uygulama maliyeti dikkate alınarak ve 20 yıllık bir süre için ömür döngüsü maliyet analizi kullanılarak optimum yalıtım kalınlıkları belirlenmiştir. Sadece ısıtma enerjisi göz önüne alındığında optimum yalıtım kalınlıkları Türkiye için 4.7 ile 16.6 cm arasında, sadece soğutma enerjisi göz önüne alındığında 0 ile 3.8 cm arasında ve toplam enerji ihtiyacı (ısıtma + soğutma) göz önüne alındığında 5.7 ile 16.6 arasında değiştiği görülmüştür. Diğer taraftan, yalıtımın geri ödeme süresi ise 3.85 ile 16.25 yıl arasında değişmektedir. Ayrıca bu çalışmada, optimum yalıtım kalınlığı ve enerji tasarrufu üzerinde etkili olan parametrelerin belirlenmesi için bir parametrik analiz de yürütülmüştür.
Anahtar Kelimeler: Optimum ısıl yalıtım kalınlığı, Enerji tasarrufu, Derece-gün.

INTRODUCTION

Energy conservation is an integral part of energy policies and it has become one of the most effective ways in the energy strategies of countries because nowadays energy is a crucial factor for the social and economic development of societies and furthermore, energy consumption is increasing rapidly due to urbanization, industrialization and population growth. This is particularly important for Turkey because it imports most of its energy and its share of imports continues to increase each year. Due to limited indigenous energy resources, Turkey has to import nearly 55-60% of its energy from abroad to meet her needs (Ogulata, 2002; Kaygusuz and Kaygusuz, 2002; Kaygusuz and Kaygusuz, 2004).

As in many countries, significant energy savings are also possible for Turkey in different fields such as industrial, residential, transportation, agricultural and conversion processes. In addition, because a considerable portion of the total energy consumption is used in the residential sector (approx. 32%), and space heating has the highest value (more than 40%) among the residential energy consumption sources (e.g. such as water heating, cooking, lighting, food refrigeration and freezing). For that reason, thermal insulation in external walls appears to be an appropriate solution in terms of energy saving measures (Mohsen and Akash, 2001; Kaygusuz and Kaygusuz, 2002; Ozkahraman and Bolatturk, 2006). In recent years, thermal insulation in the external walls of buildings has been gaining much more interest for Turkey not only because of the high cost of energy but also the environmental effect of the consumed energy.

A regulation regarding building insulation was issued in 1999 in Turkey to reduce the energy consumption in buildings (TS825, 1999). According to the regulation, 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. Natural gas consumption for heating began in 1987, and its usage has increased recently due to national energy policies. The amount of natural gas consumed in Turkey in 2008 and 2009 is about 40 billion cubic meters. According to BOTAS's projections, natural gas demand will rise to about 70 billion cubic meters by 2020 (BOTAS, 2010; DTM, 2010).

One of the methods for estimating the energy requirements for heating or cooling purposes in a building over a specified period is the degree-day (*DD*) method. Because the total number of *DD*s is the difference between the base temperature (T_b) and the mean outdoor ambient temperature, it is strongly dependent on the T_b in addition to the weather conditions. The determination of T_b depends upon various parameters such as climate conditions (e.g. temperature, humidity, precipitation and wind), building characteristics (e.g. thermal insulation, air leakage and solar gains) and personal preferences (Kadioglu vd, 2001; Buyukalaca vd, 2001). The recommended cooling base temperature is between 23 and 25.5°C for buildings without insulation and between 25.5 and 27.8°C for well-insulated buildings (Buyukalaca vd, 2001). On the other hand, the heating base temperature can be taken as 18ºC (Buyukalaca vd, 2001; Bolatturk, 2008).

Many researchers have focused on the estimation of the energy requirement in buildings, and on the effects of various design characteristics of exterior walls and insulation materials on the heating and/or cooling loads (Bolatturk, 2008; Aytac and Aksoy, 2006; Bolatturk, 2006; Kaynakli, 2008; Kaynakli, 2011, Kaynakli, 2012; Durmayaz vd, 2000; Durmayaz and Kadioglu, 2003; Ucar and Balo, 2010; Yu vd, 2009; Daouas vd, 2010). Bolatturk (2008) investigated 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 emphasized that the optimization 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. Also, depending on fuel the type, the calculations of the optimum insulation thickness were carried out for heating in Aytac and Aksoy (2006) and Bolatturk (2006) and for only one or several cities in Turkey. In these studies, in general, natural gas and coal were found to be more convenient fuels for heating than the other fuels (fuel-oil, electricity and LPG). Kaynakli (2008) investigated the residential heating energy requirements and optimum insulation thickness on a prototype building in a sample city (Bursa) in 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 type of fuel used for heating.

Durmayaz vd. (2000) and Durmayaz and Kadioglu (2003) calculated the heating energy requirement and fuel (natural gas) consumption in the biggest city centers of Turkey using the degree-hour concept, but the optimum insulation thicknesses were not mentioned in their studies. Comakli and Yuksel (2003) determined the optimum insulation thicknesses for certain cities (Erzurum, Kars, Erzincan) located in cold regions in Turkey, and they found that the optimum insulation thicknesses are 10.4, 10.7 and 8.5 cm respectively for each city when coal is used for heating. Sisman vd. (2007) investigated the optimum insulation thicknesses for external walls and roofs (ceilings) with respect to the different heating *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 optimize the insulation thickness only for certain cities in Turkey on the basis of degree-days. The optimum thicknesses of five insulation materials (expanded polystyrene, extruded polystyrene, foamed polyurethane, perlite and foamed polyvinyl chloride) were calculated on the basis of heating and cooling *DD*s by Yu vd. (2009) for a typical residential wall in China. In that study, which considered different wall orientations and surface colors, it was concluded that expanded polystyrene is the most economical insulation material because it has the highest life-cycle savings and lowest payback period. Another study considered external wall orientations is Al-Khawaja (2004), in which a comparison of total costs among four different insulation materials was carried out for light-coloured and deep-coloured surfaces in Qatar. Expanded polystyrene was also found to be the most profitable insulation material for Tunisia in the study of Daouas vd. (2010). That study concluded that the optimum thickness of insulation is 5.7 cm, which leads to energy savings of 58% with a payback period of 3.11 years. By considering the climate of Tehran, Iran, Farhanieh and Sattari (2006) investigated the variations of heat flux from/to external walls with insulation thickness for the spring, summer, fall, and winter seasons. It was emphasized that a substantial amount of energy savings can be achieved with insulation in external walls, but the optimum values for insulation were not given in that study.

Some researchers have focused on the reduction of emissions such as carbon dioxide and other greenhouse gases and on the environmental effects beside the optimum insulation thickness (Comakli and Yuksel, 2004; Dombayci, 2007; Ucar, 2010; Mahlia and Iqbal, 2010). Comakli and Yuksel (2004) investigated the environmental impact of the thermal insulation for one of the coldest provinces of Turkey, Erzurum. They determined that in case of using fuel-oil for heating, CO_2 emissions were cut by 50% when the optimum insulation thickness was used in the external walls of buildings. 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, 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%. Mahlia and Iqbal (2010) analyzed the cost benefits and emission reductions when using the optimum thickness of selected insulation materials and air gaps in building walls in the Maldives. They concluded that, without an air gap in the wall, the fiberglass-urethane has the greatest life-cycle savings and so is the most economical insulation material, whereas the fibreglass (rigid) is the least economical. Moreover, when an air gap was introduced in the composite wall, urethane was the least economical.

Above-mentioned studies related to optimize the thermal insulation thickness are based on either heating degree-days (*HDD*s) or cooling degree-days (*CDD*s). In this study, the *HDD*s and *CDD*s are considered individually and also together; the effects of these cases on insulation thickness are investigated. Moreover, the current installation cost of insulation is considered, in addition to insulation material cost, in the calculations. The saved energy by using insulation and the payback periods for each city in Turkey are presented in tabular form.

THE EXTERNAL WALL STRUCTURE AND ENERGY REQUIREMENTS

One of the most commonly used thermal insulation materials is polystyrene (Mohsen and Akash, 2001). Hence, in this study, polystyrene was chosen as the insulation material for the calculations. The structure of the wall used in this study consists of 2 cm of inner plaster (k=0.87 W/mK), 19 cm of horizontal hollow brick (k=0.45 W/mK), 3 cm of external plaster (k=0.87 W/mK) and the insulation material (k=0.035 W/mK).

The heat loss and heat gain per unit area of the wall, the properties of which are also given in Table 1, are

$$q = U(T_b - T_o) \tag{1}$$

$$q = U(T_o - T_b) \tag{2}$$

where U is the overall heat transfer coefficient, T_b and T_o are the base and the mean daily temperatures, respectively.

In terms of degree-days, the annual heating energy requirement per unit area due to the heat loss from the wall can be expressed as follows

$$E_h = 86400\, HDD\, U / \eta \tag{3}$$

where η is the efficiency of the heating system, which is assumed to be 0.93 for a typical heating system using natural gas [13]. Because of the heat gains, the annual cooling energy requirement per unit area can be written as

$$E_c = 86400\, CDD\, U / COP \tag{4}$$

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 [11,28].

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

$$U = \frac{1}{1/h_i + R_w + x/k + 1/h_o} \tag{5}$$

where h_i and h_o are the inside and outside convective heat transfer coefficients respectively, R_w is the total thermal resistance of the composite wall materials without insulation, and x and k are the thickness and thermal conductivity of insulation material, respectively. The recommended design values for the heat transfer coefficients on the inner and outer surfaces of a building are h_i = 8.29 W/m^{2}K and h_o = 34.0 W/m^{2}K [29]. The total wall thermal resistance excluding the insulation layer resistance ($R_{t,w}$) is 0.617 m^{2}K/W (see Table 1). Thus, U can be expressed as follows

$$U = \frac{1}{R_{t,w} + x/k} \tag{6}$$

Hence, the annual heating energy requirement can be rewritten as

$$E_h = \frac{86400 HDD}{(R_{t,w} + x/k)\eta} \tag{7}$$

The annual fuel consumption for heating is

$$m_f = \frac{86400 HDD}{(R_{t,w} + x/k)\eta \mathrm{LHV}} \tag{8}$$

Table 1. Parameters used in the calculations.

Parameter		Value
Wall structure		
x cm	Insulation material	k = 0.035 W/mK
2 cm	internal plaster	k = 0.87 W/mK
19 cm	hollow brick	k = 0.45 W/mK
3 cm	external 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}+0.617) W/m^{2}K
Insulation (polystyrene) (Al-Sanea vd, 2005; Bolatturk, 2008; Daouas, 2011)		
conductivity		k = 0.035 W/mK
material cost [a]		C_{ins} = 80 USD/m^3
Installation cost		C_{inst} = 9 USD/m^2
Fuel (natural gas) (Anonymous, 2010, Aytac and Aksoy, 2006)		
Price, C_f		0.386 USD/m^3
Lower heating value, LHV		34.526 x 10^6 J/m^3
Efficiency of heating system, η		0.93
Electricity		
Price, C_f		0.132 USD/kWh
Coefficient of cooling system performance, COP		2.5 (Bolatturk, 2008; Soylemez and Unsal, 1999)
Financial parameters (TCMB, 2011; TUIK, 2011)		
inflation rate, i		6%
discount rate, g		9%
lifetime, LT		20
present worth factor, PWF		15.1 (by eq. 11)

[a] 1 USD = 1.82 Turkish Liras (TL)

where LHV is the lower heating value of the fuel. In this study, natural gas is chosen as fuel because of the fact that its usage for space heating has continued to expand in recent years in Turkey. The particular values related to natural gas are given in Table 1 (Anonymous, 2010; Aytac and Aksoy, 2006).

The annual electricity energy requirement for cooling can be written as

$$E_c = \frac{86400CDD}{\left(R_{t,w} + x/k\right)COP} \tag{9}$$

ECONOMIC ANALYSIS AND OPTIMUM INSULATION THICKNESS

One of economic evaluation techniques is LCC analysis, which determines the total cost of owning and operating a facility over period of time. In this study, LCC analysis is used to calculate the total cost of heating or cooling over the lifetime of the building, which is extensively discussed in Bolatturk (2006), Al-Sanea vd, (2003), Al-Sanea vd, (2005) and Mearig vd, (1999).

It is obvious that as the thickness of the insulation material increases, the insulation cost increases, while the heating/cooling load and the energy cost 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 cost of heating or cooling. The optimum insulation thickness is the thickness at which the total cost is a minimum. Choosing a thickness value apart from the optimum one increases the total cost.

The total cost (C_t) to be considered in the optimization is the sum of the cost of insulation material ($C_{t,ins}$), the additional cost of installing the insulation (C_{ad}) and the present value of the cost of energy consumption of the heating or cooling system over the lifetime of the building ($C_{h,pv}$). Therefore, the total heating cost per unit area of wall is expressed as

$$C_t = C_{t,ins} + C_{h,pv} = C_{ins}x + C_{ad} + C_h PWF \tag{10}$$

where C_{ins} is the cost of insulation material per unit volume in USD/m^3, C_{ad} the cost of installing the insulation per unit of wall area in USD/m^2, C_h is the current yearly total cost of energy consumption for heating in USD/m^2 and PWF is the present-worth factor.

As a function of inflation rate (i), discount rate (g) and expected lifetime of building (LT in years), the PWF is calculated as (Al-Sanea vd, 2003; Hasan, 1999)

$$PWF = \left(\frac{1+i}{g-i}\right)\left[1-\left(\frac{1+i}{1+g}\right)^{LT}\right] \quad (\text{for } g \neq i) \tag{11}$$

$$PWF = \frac{LT}{1+g} \quad (\text{for } g = i) \tag{12}$$

LT is the expected lifetime, which is taken to be 20 years (Yu vd, 2009; Mahlia and Iqbal, 2010; Soylemez and Unsal, 1999; Mahlia vd, 2007). The prevailing inflation and discount rates have been taken from the Central Bank of the Republic of Turkey and Turkish Statistical Institute (TCMB, 2011; TUIK, 2011). The insulation costs (material and installation) were taken from the local insulation companies (practitioners and vendors) (Anonymous, 2011a; Anonymous, 2011b). The annual heating cost for the building depends on its fuel consumption and the fuel cost. It can be written as

$$C_h = \frac{86400\, HDD\, C_f}{\left(R_{t,w} + x/k\right)\eta\ \mathrm{LHV}} \tag{13}$$

where C_f is the fuel cost in USD/m^3, which is given in Table 1. Finally, the total cost of heating the insulated building in present dollars can be rewritten as follows

$$C_{t,h} = C_{t,ins} + C_{h,pv} = C_{ins}x + C_{ad} + \frac{86400\, HDD\, C_f}{\left(R_{t,w} + x/k\right)\eta\ \mathrm{LHV}} PWF \tag{14}$$

The optimum insulation thickness is obtained by minimizing Eq. (14). The partial derivative of the equation of $C_{t,h}$ with respect to the insulation thickness (x) is taken. Equating to zero of the first derivative function yields the $x_{opt,h}$, which is obtained as follows

$$x_{opt,h} = \left(\frac{86400\, HDD\, C_f\ PWF\, k}{\eta\ LHV\ C_{ins}}\right)^{1/2} - R_{t,w}k \tag{15}$$

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

$$C_{t,c} = C_{ins}x + C_{ad} + \frac{86400 CDD\, C_e PWF}{\left(R_{t,w} + x/k\right)COP} \tag{16}$$

$$x_{opt,c} = \left(\frac{86400\, CDD\, C_e\ PWF\, k}{COP\, C_{ins}}\right)^{1/2} - R_{t,w}k \tag{17}$$

where C_e is the cost of the electricity because the cooling system is supplied with electricity. The cost of electricity expressed as USD/kWh is given in Table 1.

Above equations are based on only the heating or cooling energy, respectively. But, the annual total cost of energy is the sum of the heating and cooling energy costs. Therefore, the annual total cost ($C_{t,a}$) and the optimum insulation thickness considering the annual total cost ($x_{opt,a}$) can be calculated by

$$C_{t,a} = C_{ins}x + C_{ad} + \frac{86400 HDD\, C_f\, PWF}{\left(R_{t,w} + x/k\right)Hu\,\eta} + \frac{86400 CDD\, C_e PWF}{\left(R_{t,w} + x/k\right)COP} \tag{18}$$

$$x_{opt,a} = 293.94\left(\frac{PWF}{C_{ins}}\right)^{1/2} \left(\frac{k\left(C_f\, HDD/\eta\ Hu + C_e CDD/COP\right)}{C_{ins}}\right)^{1/2} - R_{t,w}k \tag{19}$$

Insulation used on external wall is dependent on 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.

The heating and cooling energy cost savings (*ECS*) over the life of the system is calculated by the difference between the costs for heating and cooling in uninsulated and insulated buildings. The savings of heating and cooling energy cost per unit area of wall with the optimum insulation thickness can be determined by

$$ECS = \left[C_{h,pv} - C_{c,pv}\right]\ (x=0) - \left[C_{h,pv} - C_{c,pv}\right]\ (x = x_{opt,a}) \tag{20}$$

The payback period can be calculated by dividing the total insulation cost, which includes material and installation costs, by the yearly energy cost savings, which is given as follows

$$Payback = \frac{\left(C_{ins}x_{opt,a} + C_{ad}\right)}{ECS/LT} \tag{21}$$

Payback period indicates the number of years necessary to recover the investment.

RESULTS AND DISCUSSION

Particular data for cities in Turkey are given in Table 2. In this table, in addition to topographic features of the cities, the *DD* values used in the calculations and the climatic (degree-day) zones are presented [6,10]. As can be seen from Table 2, there are considerable variations in the *DD* values among cities in Turkey because of geographical and meteorological differences. For instance, the *HDD* value for Iskenderun (located in southern Turkey and in the eastern Mediterranean Sea) is 690, while it is 2677 for Ankara (the capital of Turkey, which is located in the middle of Anatolia), 5137 for Ardahan (located in northeastern of Turkey). This means that a building in Ardahan requires 7.4 times (1.9 times in Ankara) more heating energy than a building in Iskenderun with the same characteristics.

Table 2. Topographic features, climate zones and degree-days for cities in Turkey [6,10].

City	Longitude	Latitude	Altitude (m)	Zone	*HDD*	*CDD*
Adana	35.18	36.59	20	1	874	255
Adiyaman	38.17	37.45	678	2	1695	360
Afyon	30.32	38.45	1034	3	2828	2
Agri	43.08	39.31	1585	4	4423	1
Aksaray	34.03	38.23	980	3	2626	11
Amasya	35.51	40.39	412	2	2210	14
Ankara	32.53	39.57	894	3	2677	8
Antalya	30.42	36.53	42	1	1083	164
Ardahan	42.42	41.08	1829	4	5137	0
Artvin	41.49	41.10	597	3	2429	5
Aydin	27.50	37.51	57	1	1213	170
Balikesir	27.52	39.39	147	2	1914	20
Bartin	32.21	41.38	30	2	2226	1
Batman	41.10	37.52	540	2	1823	318
Bayburt	40.15	40.16	1550	4	4149	0
Bilecik	29.58	40.09	526	3	2397	7
Bingol	40.30	38.52	1177	3	2838	83
Bitlis	42.06	38.22	1559	4	3311	6
Bolu	31.36	40.44	742	3	2821	0
Burdur	30.20	37.40	967	3	2351	14
Bursa	29.04	40.11	100	2	1920	12
Canakkale	26.24	40.08	3	2	1789	25
Cankiri	33.37	40.36	751	3	2864	4
Corum	34.58	40.33	798	3	2958	0
Denizli	29.05	37.47	428	2	1627	120
Diyarbakir	40.12	37.55	660	2	2142	242
Edirne	26.34	41.40	48	2	2224	16
Elazig	39.13	38.40	1105	3	2653	73
Erzincan	39.30	39.44	1215	4	3047	8
Erzurum	41.16	39.55	1869	4	4827	0
Eskisehir	30.31	39.46	800	3	3049	0
Gaziantep	37.22	37.05	855	2	2009	157
Giresun	38.24	40.55	38	2	1765	3
Gumushane	39.27	40.27	1219	4	3234	2
Hakkari	43.46	37.34	1720	4	3470	18
Hatay	36.07	36.15	100	1	1119	139
Igdir	44.02	39.56	858	3	2764	43
Iskenderun	36.07	36.37	3	1	690	175
Isparta	30.33	37.45	997	3	2607	4
Istanbul	29.05	40.58	39	2	1865	6
Izmir	27.10	38.24	25	1	1188	147
K.Maras	36.56	37.36	549	2	1653	210
Karaman	33.14	37.11	1025	3	2698	7
Kars	43.05	40.36	1775	4	4772	0
Kastamonu	33.46	41.22	791	4	3112	0
Kayseri	35.29	38.43	1068	4	3113	1
Kilis	37.05	36.44	638	2	1554	224
Kirikkale	33.30	39.50	725	3	2609	10
Kirklareli	27.13	41.44	232	3	2274	20
Kirsehir	34.10	39.08	985	3	2857	4
Kocaeli	29.54	40.46	76	2	1786	18
Konya	32.30	37.52	1028	3	2836	5
Kutahya	29.58	39.24	969	3	2880	0
Malatya	38.18	38.21	998	3	2461	103
Manisa	27.26	38.36	71	2	1535	171
Mardin	40.44	37.18	1080	2	2004	315
Mersin	34.36	36.49	5	1	852	124
Mugla	28.21	37.12	646	2	1879	81
Mus	41.31	38.44	1283	4	3563	25
Nevsehir	34.40	38.25	1260	3	3033	2
Nigde	34.40	37.59	1208	3	2856	2
Ordu	37.52	40.59	4	2	1804	3
Rize	40.30	41.02	4	2	1820	1
Sakarya	30.25	40.47	30	2	1833	10
Samsun	36.20	41.17	44	2	1826	0
Siirt	41.56	37.56	875	2	1958	311
Sinop	35.10	42.02	32	2	1879	1
Sivas	37.01	39.49	1285	4	3444	1
Sanliurfa	38.46	37.08	547	2	1503	429
Tekirdag	27.29	40.59	4	2	2032	3
Tokat	36.54	40.18	608	3	2399	5
Trabzon	39.43	41.00	30	2	1724	1
Tunceli	39.32	39.06	979	3	2716	85
Usak	29.29	38.40	919	3	2414	9
Van	43.41	38.28	1725	4	2476	1
Yalova	29.16	40.39	2	2	1843	4
Yozgat	34.49	39.50	1298	4	3422	0
Zonguldak	31.48	41.27	136	2	2020	2

Using the *HDD* and *CDD* values in the Table 2, the optimum thermal insulation thicknesses are calculated by Eq. (15), (17) and (19) for heating, cooling and annual (heating + cooling) energy requirements, separately; and all results are presented in Table 3. When all cities are considered together, the optimum insulation thicknesses for only heating energy requirements ($x_{opt,h}$) vary in a wide range from 4.7 to 16.6 cm. As the heating energy requirement (i.e. *HDD*) increases, the needed insulation thickness is increases as well. For example, while the $x_{opt,h}$ is 4.7 cm for Iskenderun located in the first degree-day zone in Turkey (*HDD* is only 690), it is 16.6 cm for Ardahan located in the fourth degree-day zone (*HDD* is 5137). This means that while a building in Ardahan requires approximately 3.5 times thicker insulation than a building in Iskenderun.

The optimum insulation thicknesses for cooling ($x_{opt,c}$) are also shown in Table 3. These values were calculated with respect to only the cooling energy requirement (in other words, the *CDD*). The $x_{opt,c}$ values vary in a relatively narrow range of 0 to 3.8 cm. The $x_{opt,c}$ values are higher in warm cities, which have high *CDD* values. There is not an optimum value for the insulation thickness in the cities having low *CDD*, because the total cost increases continuously with the insulation thickness due to the insulation material cost. Therefore, $x_{opt,c}$ values of 0 cm are obtained for these cities as can be seen from Table 3.

It is clearly seen from the Table 3 that the optimum insulation thicknesses for heating are higher than that for cooling. For that reason, while calculating the optimum insulation thickness for buildings, the determinant factor is the heating energy cost for Turkey. But, the heating energy requirement is not enough alone. The annual energy requirements (heating + cooling) should be considered. By considering the annual energy requirement, the optimum insulation thicknesses ($x_{opt,a}$) vary between 5.7 and 16.6 cm. The optimum insulation thickness of 5.7 cm is obtained for Iskenderun (*HDD*=690, *CDD*=175), and 16.6 cm is obtained for Ardahan (*HDD*=5137, *CDD*=0). For Iskenderun, while $x_{opt,h}$ is 4.7 cm, $x_{opt,a}$ is 5.7 cm due to cooling energy. For that reason, the insulation thickness calculations should be carried out on the basis of annual (total) energy requirement instead of only seasonal. In the literature, most of studies dealing with optimum insulation thickness are based on either heating loads [13-18] or cooling loads [37-39]. Only several studies consider both annual heating and cooling loads [11,19,45]. On the other hand, in this study, apart from the mentioned studies, the heating and cooling energy requirements are taken into consideration both individual and together in order to show the influence of seasonal energy requirements on insulation thickness.

Annual energy savings rates are also shown in Table 3. The energy savings rate means the decrease rate in heat loss and gains (i.e. heating and cooling transmission loads). The amount of energy savings by using the $x_{opt,a}$ varies between 72.6 and 88.5% depending on cities. Energy savings is directly related to climatic conditions, a considerable energy savings can be achieved in the cities having high annual energy requirements when the optimum insulation thickness is applied to external walls.

Considering all cities in Turkey, the average energy savings rate of 83% can be achieved by using the optimum insulation thickness ($x_{opt,a}$ values) in external walls of buildings. Because of the fact that the total number of buildings and their structures are not the same in each city, this gives a rough estimate, and the actual value may be slightly more or less. But, the predicted value indicates technically the maximum potential savings achievable. It is noted that the predicted value is an important indicator because it shows the potential amount of annual (heating and cooling) energy savings by using the optimum insulation thickness.

Payback period indicates the number of years necessary to recover the investment. The payback periods given in Table 3 have been calculated in case of using optimum insulation thicknesses based on the annual energy requirements. They vary between 3.85 and 16.25 years. In the cities having high annual energy requirements for heating and cooling, although the insulation thicknesses are high, the payback periods are short such as the cities of Ardahan, Erzurum and Kars.

Fig. 1 (a)-(f) presents the results of a parametric analysis which is carried out in order to investigate the effect of economic parameters on the optimum insulation thickness and energy savings. The parameters considered in this analysis are, respectively, building lifetime, inflation rate, discount rate, cost of insulation material, cost of natural gas, and thermal conductivity of insulation material. In addition, Istanbul is taken as a sample city in the parametric calculations. It is noted that the above-mentioned parameters have significant effect on optimum insulation thickness and energy savings. The optimum thickness increases with increasing the lifetime, inflation rate, fuel cost, or thermal conductivity of insulation material, and decreases with increasing the discount rate or the insulation material cost. Since the installation cost of insulation does not depend on the thickness, there is not any effect on the optimum insulation thickness as can be seen in eq. (19). Similar trends and conclusions were obtained by Al-Sanea and Zedan [40] and Daouas [41], which confirm the results of the present investigation carried out under different energy costs and climatic conditions.

5. CONCLUSIONS

In this study, considering energy, insulation (material and installation) and total costs, the optimum thermal insulation thicknesses have been determined by using the optimization method based on life-cycle cost analysis for heating and cooling energy requirements

Table 3. The optimum insulation thicknesses and payback periods.

City	Heating and cooling degree-days, *HDD / CDD*	Opt. ins. thickness for heating, $x_{opt,h}$ (m)	Opt. ins. thickness for cooling, $x_{opt,c}$ (m)	Opt. ins. thickness for annual, $x_{opt,a}$ (m)	Energy savings (%)	Payback period (years)
Adana	874 / 255	0.056	0.025	0.069	76.1	12.62
Adiyaman	1695 / 360	0.086	0.033	0.099	82.2	7.60
Afyon	2828 / 2	0.118	0	0.118	84.5	6.05
Agri	4423 / 1	0.153	0	0.153	87.6	4.30
Aksaray	2626 / 11	0.113	0	0.113	84.0	6.39
Amasya	2210 / 14	0.102	0	0.102	82.6	7.33
Ankara	2677 / 8	0.114	0	0.114	84.1	6.30
Antalya	1083 / 164	0.065	0.015	0.072	77.0	11.75
Ardahan	5137 / 0	0.166	0	0.166	88.5	3.85
Artvin	2429 / 5	0.108	0	0.108	83.3	6.82
Aydin	1213 / 170	0.070	0.016	0.077	78.2	10.74
Balikesir	1914 / 20	0.093	0	0.094	81.3	8.23
Bartin	2226 / 1	0.102	0	0.102	82.6	7.33
Batman	1823 / 318	0.090	0.030	0.102	82.5	7.38
Bayburt	4149 / 0	0.147	0	0.147	87.2	4.51
Bilecik	2397 / 7	0.107	0	0.107	83.2	6.89
Bingol	2838 / 83	0.118	0.005	0.121	84.8	5.87
Bitlis	3311 / 6	0.129	0	0.129	85.7	5.34
Bolu	2821 / 0	0.118	0	0.118	84.5	6.07
Burdur	2351 / 14	0.105	0	0.106	83.1	6.98
Bursa	1920 / 12	0.093	0	0.094	81.3	8.24
Canakkale	1789 / 25	0.089	0	0.090	80.7	8.67
Cankiri	2864 / 4	0.119	0	0.119	84.6	5.99
Corum	2958 / 0	0.121	0	0.121	84.9	5.84
Denizli	1627 / 120	0.084	0.010	0.089	80.4	8.87
Diyarbakir	2142 / 242	0.100	0.023	0.108	83.3	6.82
Edirne	2224 / 16	0.102	0	0.103	82.6	7.29
Elazig	2653 / 73	0.113	0.003	0.116	84.3	6.20
Erzincan	3047 / 8	0.123	0	0.123	85.1	5.70
Erzurum	4827 / 0	0.160	0	0.160	88.1	4.03
Eskisehir	3049 / 0	0.123	0	0.123	85.1	5.71
Gaziantep	2009 / 157	0.096	0.015	0.101	82.4	7.41
Giresun	1765 / 3	0.089	0	0.089	80.4	8.89
Gumushane	3234 / 2	0.127	0	0.128	85.5	5.45
Hakkari	3470 / 18	0.133	0	0.133	86.1	5.14
Hatay	1119 / 139	0.066	0.013	0.072	77.1	11.71
Igdir	2764 / 43	0.116	0	0.118	84.5	6.07
Iskenderun	690 / 175	0.047	0.017	0.057	72.6	16.25
Isparta	2607 / 4	0.112	0	0.112	83.9	6.45
Istanbul	1865 / 6	0.092	0	0.092	81.0	8.47
Izmir	1188 / 147	0.069	0.014	0.075	77.7	11.10
K.Maras	1653 / 210	0.085	0.020	0.093	81.2	8.33
Karaman	2698 / 7	0.115	0	0.115	84.2	6.27
Kars	4772 / 0	0.159	0	0.159	88.1	4.07
Kastamonu	3112 / 0	0.125	0	0.125	85.2	5.62
Kayseri	3113 / 1	0.125	0	0.125	85.2	5.61
Kilis	1554 / 224	0.082	0.022	0.090	80.7	8.64
Kirikkale	2609 / 10	0.112	0	0.113	83.9	6.43
Kirklareli	2274 / 20	0.103	0	0.104	82.8	7.15
Kirsehir	2857 / 4	0.118	0	0.119	84.6	6.00
Kocaeli	1786 / 18	0.089	0	0.090	80.6	8.72
Konya	2836 / 5	0.118	0	0.118	84.6	6.03
Kutahya	2880 / 0	0.119	0	0.119	84.7	5.97
Malatya	2461 / 103	0.108	0.008	0.112	83.8	6.50
Manisa	1535 / 171	0.081	0.016	0.088	80.3	8.99
Mardin	2004 / 315	0.096	0.030	0.106	83.2	6.93
Mersin	852 / 124	0.055	0.011	0.061	74.0	14.72
Mugla	1879 / 81	0.092	0.004	0.095	81.5	8.09
Mus	3563 / 25	0.135	0	0.136	86.3	5.03
Nevsehir	3033 / 2	0.123	0	0.123	85.1	5.73
Nigde	2856 / 2	0.118	0	0.119	84.6	6.00
Ordu	1804 / 3	0.090	0	0.090	80.6	8.72
Rize	1820 / 1	0.090	0	0.090	80.7	8.67
Sakarya	1833 / 10	0.091	0	0.091	80.8	8.57
Samsun	1826 / 0	0.090	0	0.090	80.7	8.65
Siirt	1958 / 311	0.094	0.029	0.105	83.0	7.05
Sinop	1879 / 1	0.092	0	0.092	81.0	8.44
Sivas	3444 / 1	0.132	0	0.132	86.0	5.19
Sanliurfa	1503 / 429	0.080	0.038	0.096	81.7	7.93
Tekirdag	2032 / 3	0.097	0	0.097	81.8	7.90
Tokat	2399 / 5	0.107	0	0.107	83.2	6.89
Trabzon	1724 / 1	0.087	0	0.087	80.2	9.08
Tunceli	2716 / 85	0.115	0.005	0.118	84.5	6.07
Usak	2414 / 9	0.107	0	0.107	83.3	6.84
Van	2476 / 1	0.109	0	0.109	83.5	6.73
Yalova	1843 / 4	0.091	0	0.091	80.8	8.56
Yozgat	3422 / 0	0.132	0	0.132	85.9	5.22
Zonguldak	2020 / 2	0.096	0	0.096	81.7	7.94

both separately and together. In addition to optimum insulation thicknesses, the amount of energy saved and the payback periods have been calculated and a parametric analysis has been carried out.

The results showed that the optimum thermal insulation thicknesses for only heating varied between 4.7 and 16.6 cm, varied between 0 and 3.8 cm for only cooling energy, and varied between 5.7 and 16.6 cm for total annual (heating and cooling) energy depending on the city. Because the *HDD* values are higher than the *CDD* for all cities, thicker optimum insulation thicknesses are obtained for heating. For that reason, the critical point for determining the insulation thickness is the heating energy requirement and heating cost. Especially in the cities having cold climate, substantial energy savings can be obtained by using proper insulation. For example, the energy savings rate can be reached to 88.5% for Ardahan by using the $x_{opt,a}$ thermal insulation value. The payback periods in Turkey varied between 3.85 and 16.25 years for considering annual energy requirements. The payback period was found shorter in the cities having greater annual energy requirements.

Moreover, in this study, a parametric analysis is carried out in order to investigate the effective parameters on the optimum insulation thickness and energy savings. The analysis results show that the optimum insulation values may change significantly with using different values of parameters in the economic analysis. The optimum insulation thickness is found to increase with the cost of natural gas, building lifetime, thermal conductivity of insulation material and inflation rate; and decrease with increasing cost of insulation material and discount rate.

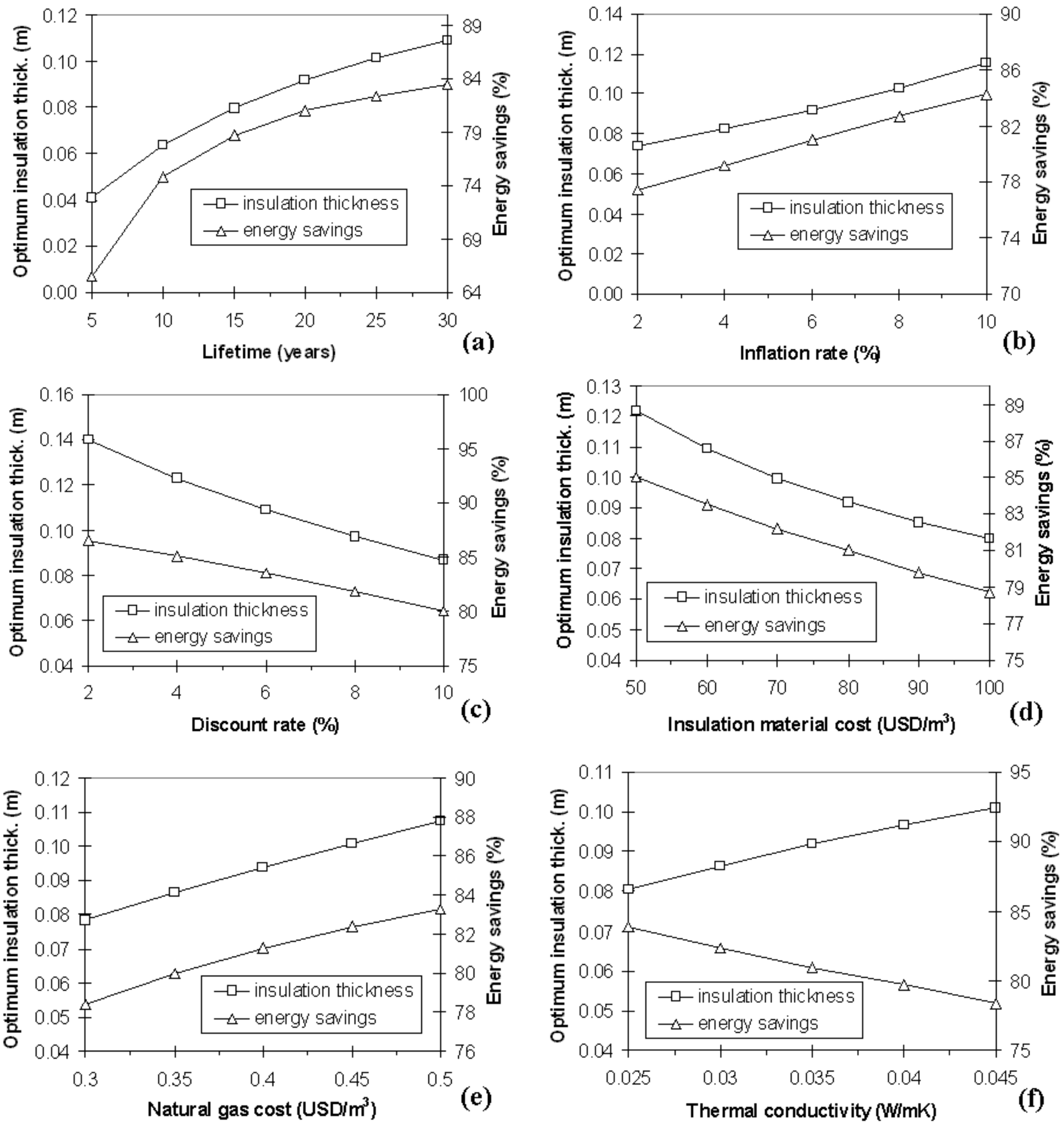

Figure 1. Effect of economic parameters on optimum insulation thickness and energy savings. (a) lifetime, (b) inflation rate, (c) discount rate, (d) cost of insulation material, (e) cost of natural gas, (f) thermal conductivity of insulation material.

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