International Scientific Journal
Environmental Science
http://environment.scientific-journal.com

Determination of Optimum Parameters for Walls with Phase Change Materials

Alptug Yataganbaba
Department of Mechanical Engineering
Hitit University
Corum, Turkey
alptugyataganbaba@gmail.com

Irfan Kurtbas
Department of Mechanical Engineering
Hitit University
Corum, Turkey
ikurtbas@gmail.com

***Abstract*— It has been acknowledged that the majority of energy consumption takes places in residences. In order to minimize energy consumption, it is necessary to optimize insulation cost in buildings. Recently, phase change materials (PCMs) in sandwich panels have been placed into the building wall or surface instead of conventional insulation materials. Therefore, the energy is stored within the walls and insulation is made by using PCM's low heat conduction coefficient. In this study, the optimum insulation thickness was determined by taking weather conditions of three different regions in Turkey into consideration. In addition, heating loads were calculated according to a single value of the solar radiation absorption rate of the building's exterior surface. The P_1-P_2 method, which includes heating load, and the economical method was used when calculating the optimum insulation thickness. Accordingly, the optimum insulation thickness, energy saving and payback periods for three different regions were also determined by using economic data, such as interest, inflation and lifetime. In addition to that, the results were compared with regards to standard insulation and without radiation condition.**

Keywords*— *insulation, phase change material

I. INTRODUCTION

The depletion of fossil fuels will be a reality in the near future. Therefore, the efficient use of the remaining fossil fuels has gained more importance day by day. At the same time, energy savings have become mandatory nowadays because of the environmental pollution caused by unconscious energy consumption. Becoming more energy efficient is an important first step in reducing our impact on the environment. To minimize waste heat released in everyday life by making lifestyle changes is the cheapest, easiest and optimum way to gain more useful energy with the least environmental impact. These small changes can reduce energy consumption directly. Energy efficiency can be achieved in a variety of ways. One of these ways is to combine different materials or enhance product specifications when designing new buildings to take advantage of natural resources and minimize energy waste. It is very important because, buildings are responsible for at least 40% of energy use in most countries. One of the building design practices that achieves energy efficiency is proper insulation. For instance, almost 30% of total energy and around 40% of electricity consumption is used in buildings in Turkey Because of that, the researches for the improvement of energy efficiency in buildings are of great importance in Turkey. A significant portion of this consumption can be decreased by the proper insulation method. In general, there is no insulation in the majority of the buildings in Turkey. It has been observed even in buildings with insulation that inefficient and low cost materials are used. In our country, heat loss or gain in buildings is much higher compared to European countries with similar climatic conditions due to a lack of awareness about thermal insulation. This situation caused a sharp increase in insulation demand, observed for years and years. Therefore, it is very important to choose the best type insulation material and apply the optimum thickness of insulation considering investment and operating costs for insulation applications in buildings [1].

Insulation costs will increase while decreasing the heat gains and losses significantly with increasing thickness of the insulation to be applied to the building wall. Therefore, it is necessary to make a cost analysis. Optimum insulation thickness depends on many economic parameters. Annual heating and cooling loads vary according to climatic zones. Therefore, while arranging the optimum insulation thickness calculations it should be determined in advance which will be the main factor: heating or cooling load [2].

The energy consumed for cooling purposes in buildings increases greatly due to a greater cooling season yearly in warm climates. Thus, while calculating the optimum insulation thickness cooling load should be taken into account. When viewed from this aspect, it can be noticed that there are many studies in the literature related to the calculation of optimum insulation thickness. In a study which set out to determine sun-air temperatures considering the effect of solar radiation, Bolattürk [2] evaluated separately according to light and dark colored surfaces and also different aspects. Overall, this study highlighted the need to evaluate the optimum insulation thickness according to the cooling load in buildings in hot climate regions. Al-Khawaja [3] performed a study to determine optimum insulation thickness for four insulation materials considering both energy and total costs in hot countries such as Qatar. Dombaycı et al. [4] calculated an optimum thickness for five different energy sources and two different insulation materials for the city of Denizli. Life cycle cost analysis was used for optimization. The results obtained

from analysis showed that coal and expanded polystyrene are the most proper energy source and insulation material, respectively. On the other hand, the optimum insulation thickness was obtained as 14.09 $/m^2. In another study, optimum insulation thicknesses of the external walls using rock wool as insulation material, energy savings and payback periods were calculated by Gölcü et al. [5]. The coal and fuel oil were used for heating in the buildings in the city of Denizli located in the III. climate zone of Turkey. They concluded that the optimum insulation thickness, the energy saving, and payback period were obtained 0.048 m, 42%, and 2.4 years, respectively. Comaklı et al. [6] developed a steady state heat transfer model by using the degree-days values. Their study was based on the life cycle cost model to determine an optimum insulation thickness for the cities of Erzurum, Kars, and Erzincan located in the IV. degree-days region of Turkey according to the standard (TS 825) for thermal insulation in buildings. They determined that the optimum insulation thicknesses were 0.104, 0.107 and 0.085 m, respectively, for each city when coal was used for heating. To better understand the mechanisms of thermal insulation and its effects, Bolatturk [7] analyzed the use of insulation on external walls of building and the payback period for different fuel types. The calculations in this study were performed using heating degree-days concept for 16 cities from four climate zones in Turkey. Polystyrene was used as an insulation material. The results indicated that the optimum insulation thickness varied between 2-17 cm, energy savings between 22-79%, and payback periods between 1.3-4.5 years. A broader perspective was adopted by Ucar and Balo [8], who argue that the optimum insulation thicknesses, energy savings and payback periods significantly depend on the regions, insulation material and fuel types. In their study, the four different cities of Turkey; Ağrı, Elazığ, Kocaeli and Aydın were selected. The P_1-P_2 method was used to calculate desired parameters using four different fuels and four different insulation materials. The results showed that the optimum insulation thickness ranged from 1.06 to 7.64 cm, energy savings varied from 19 to 47 $/m^2 and payback periods were in the range of 1.8–3.7 years. In a similar study, Gurel et al. [9] calculated optimum thickness and energy saving for heating and cooling loads in Aydın, Edirne, Malatya and Sivas, the selected cities from different climatic zones. XPS and EPS were selected as external wall insulation material. Natural gas and electricity were used for heating as fuel. The results obtained from analysis indicated that optimum thickness varied between 0.036 and 0.1m, energy saving between 12.08TL/m^2 and 58.28TL/m^2, and payback periods between 1.5 and 2.52 years.

In this study, the optimum insulation thickness was calculated for three different cities that have different temperature degree-days value. The cities covered in this study are shown on the map in Fig. 1. Primarily, heating loads were calculated according to the various values of solar radiation absorption rate of building external walls. The P_1-P_2 method, which is the economic method for the calculation of optimum thickness was used. Accordingly, optimum insulation thickness, energy savings, payback periods were determined using some economic data such as interest, inflation and lifetime for all selected cities. Total heat transfer coefficient (U) values for the exterior wall were calculated according to solar radiation and 10 cm thick phase change material (Calcium Chloride Hexahydrate).

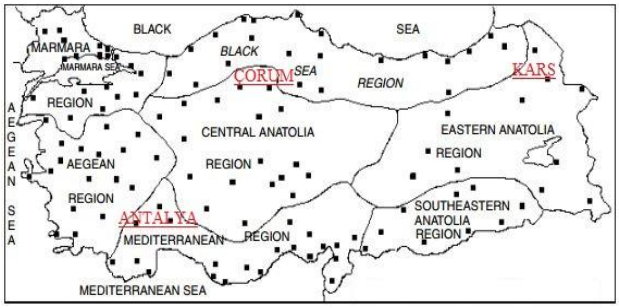

Fig. 1. Climate zones of Turkey and selected cities in this study

II. Heat loss in buildings and the annual energy needs

Many methods have been developed by ASHRAE for calculation the heating and cooling loads in buildings. A stable approach, degree-days method is the simplest and most intuitive way to predict annual energy consumption among all of these methods. Degree-day is a tool that can be used in the assessment and analysis of weather related energy consumption in buildings. The indoor and outdoor temperature must be known for determining heating and cooling loads. In these calculations, more delicate results were obtained by adding the effect of sun radiation to the indoor heat gains. In this study, hourly temperature and solar radiation data belonging to the cities in the first degree-day region was provided from meteorology. The number of annual heating degree-hours (HDH) values in case the outdoor temperature is lower than the balance point temperature is determined from;

$$HDH = (1\,year)\sum_1^{365}(1\,day)\sum_1^{24}(T_b - T_{sa})^+ \tag{1}$$

where T_b (°C) is the base temperature and T_{sa} (°C) is the solar-air temperature. The sign "+" above the parenthesis shows that only positive values are taken into account. However, if the solar air temperature less than the base temperature, namely $T_{sa}>T_b$, the annual cooling degree-hours (CDH) values can be calculated as shown;

$$CDH = (1\,year)\sum_1^{365}(1\,day)\sum_1^{24}(T_{sa} - T_b)^+ \tag{2}$$

The heat flow to the external wall of a building exposed to solar radiation can be expressed as follows [11].

$$\begin{aligned} Q_{surf} &= Q_{conv+rad} + Q_{sun} - Q_{rad,modifed} \\ &= h_0 A(T_0 - T_s) + a_s A q_{sun} - \varepsilon A\sigma(T_0^4 - T_{surr}^4) \\ &= h_0 A(T_{sa} - T_s) \end{aligned} \tag{3}$$

where T_o is the outside air temperature, T_s is the wall surface temperature, α_s is the solar absorptivity, h_o is the combined heat transfer coefficient for convection and radiation at the external surface, q_{sun} is the solar radiation on the wall surface

and ε is the emissivity of the surface. As a result, the sol-air temperature including the effect of solar radiation can be expressed as follows;

$$T_{sa} = T_0 + \frac{\alpha_s}{h_0} q_{sun} - \frac{\varepsilon\sigma(T_0^4 - T_{surr}^4)}{h_0} \quad (4)$$

Heat transfer to the surface in the form of convection and radiation can be expressed by the first term of equation (3) when ambient air temperature in the surrounding environment is equal to the average surrounding surface and sky temperature, namely (T_o=T_{surr}). Otherwise ($T_o \neq T_{surr}$), the last term of the equation, can be expressed as the correction factor for radiation heat transfer. The correction factor can be taken as approximately zero for vertical wall surfaces and 4°C for horizontal surfaces from ASHRAE. In this study, the last term for vertical wall surfaces are eliminated because the temperatures taken are equal.

Heating degree-days (HDD) values for the city of Antalya, Çorum and Kars is shown in Fig. 2. The chosen value of the base temperature is an important parameter in calculating heating and cooling loads according to the degree-hours method. In the calculations, the base temperature is chosen as 18°C for heating load and 26°C for cooling load. Also, the combined heat transfer coefficient is taken to be 17 W/m^{2}C, the solar absorptivity of the outdoor wall surface α_s is selected to be equal to 0.9 for dark colored surfaces, 0.45 for light colored surfaces. After that heating degree-days values are calculated according to the summer design values of the ratio (α_s/h_o =0.039). It is observed that heating degree-hour values are higher during the colder months of the year. In addition, the heating loads are negligible during the spring and summer in cities in hot climate regions (Fig.2). Therefore, it can be said that there is hardly any need for heating in this period.

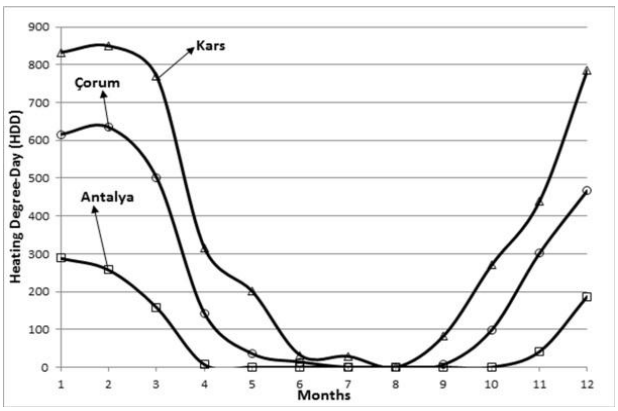

Fig. 2. Variation of monthly average heating degree-days for selected cities

Significant differences in the heating load are observed when considering solar radiation. Degree-day cooling loads in cases without radiation are generally seen starting from the 4th month (April) to the 10th month (October). It reaches the highest value especially in the middle of the summer. Radiation cooling loads are spread over all months in a significant way. Besides, the increase of cooling degree-days values are distinctly observed with increasing αs/ho values (darkening of the surface) under the influence of solar radiation. Thus, the effect of solar radiation that is absorbed by walls should be considered [12].

Most of the heat loss from a building occurs by conduction through the building components such as external walls, ceiling, roof and floor due to insufficient loft and cavity wall insulation. The heat loss rates vary according to architecture, heat insulation condition and the characteristics of the building materials used. In this study, we calculate optimum insulation thickness considering heat losses from external walls.

The heat loss from a unit area of external wall is calculated from the following equation;

$$q = U(T_b - T_{sa}) \quad (5)$$

where U (W/m^{2}K) is the overall heat transfer coefficient.

The overall heat transfer coefficient, U_{un} for a typical wall without insulation is calculated as follows;

$$U_{un} = \frac{1}{R_i + R_w + R_o} = \frac{1}{R_{tw}} \quad (6)$$

where R_i and R_o (m^{2}K/W) are the inside and outside air film thermal resistances, respectively. R_w is the total thermal resistance of non-insulated wall layers, R_{tw} is the total heat resistance of non-insulated wall.

The thermal resistance of insulation layer is given by;

$$R_{ins} = \frac{x}{k} \quad (7)$$

where x is the thickness of the insulation material, k (W/mK) is the thermal conductivity of the insulation material. The difference of total heat transfer coefficient between insulated and non-insulated wall is obtained from the following equation;

$$\Delta U = U_{un} - U_{ins} = \frac{1}{R_{tw}} - \frac{1}{R_{tw} + \frac{x}{k}} \quad (8)$$

The annual amount of energy expended for heating purposes to meet the heat loss occurring from insulated or non-insulated exterior walls of the building is calculated as follows;

$$E_{A,H} = \frac{C_F U}{LHV \eta_s} HDH \quad (9)$$

where C_F (\$/m^3) is the cost of fuel used for heating, LHV (J/m^3) is the lower heating value, η_s is the efficiency of system. In the building and construction industry, life-cycle cost analysis (LCCA) is applied to quantifying costs of whole buildings, systems, and/or building components and materials. LLCA used in this study computes the total cost of heating over the lifetime of the building. The total heating cost over a lifetime of N years should be evaluated with the present worth

factor (PWF). The PWF value depends on interest rate (i), inflation rate (d) and insulation life (N). It is possible to calculate the present worth value of the amount of net energy savings via insulation using the P_1-P_2 method [13]. P_1 is the ratio in years of the present value of the life-cycle fuel savings to the first-year fuel savings [13]. It takes into account the inflation of fuel prices over time as well as the discounting of future fuel savings according to the opportunity cost of capital:

$$P_1(N,i,d) = \sum_{J=1}^{N} \frac{(1+i)^{j-1}}{(1+d)^j} \begin{cases} \frac{1}{d-i}\left[1-\left(\frac{1+i}{1+d}\right)^N\right] & i \neq d \\ \frac{N}{1+i} & i = d \end{cases} \quad (10)$$

The factor P_2 is the ratio of the life-cycle cost incurred over the useful life of the project against the initial capital investment, which can be calculated by

$$P_2 = 1 + P_1 M_s - R_V(1+d)^{-N} \quad (11)$$

In equation (11), M_s is the ratio of first year miscellaneous costs; R_v is the ratio of the resale value at the end of the economic period to the initial investment. Accordingly, if maintenance and labor costs are assumed to be zero, P_2 value can be taken as 1 [13]. In this study, P_2 is taken 1 for without PCM wall and 1.2 for PCM wall. The insulation cost per unit area is expressed as;

$$C_{ins} = C_1 x \quad (12)$$

where C_{ins} is the cost of insulation material in $/m^3 and x is the insulation thickness in m. Energy savings obtained for heating purpose over a lifetime per unit area according to P_1-P_2 method can be calculated as follows;

$$S_H = \frac{P_1 C_F \Delta U}{LHV \eta_s} HDH - P_2 C_i x \quad (13)$$

The optimum insulation-thickness for heating, which makes the total cost a minimum, is calculated as;

$$x_{op,H} = \left(\frac{P_1 C_F k\, HDH}{P_2 C_i\, LHV \eta_s}\right)^{1/2} - R_{tw} k \quad (14)$$

The payback period is defined as the ratio of the energy cost of the non-insulated building to the energy savings. In order to calculate the payback period for a specific insulation material, the net saving should be set equal to zero. This leads to equation (15):

$$N_{P,H} = \frac{ln\left[1 - \frac{P_2 C_i\, LHV \eta_s (R_{tw} x + R_{tw}^2 k(d-i))}{C_F HDH}\right]}{ln\left(\frac{1+i}{1+d}\right)} \quad (15)$$

where $N_{P,H}$ (year) indicated the payback period for heating. The total cost of heating over the lifetime per unit area the insulated building in present is given by;

$$C_{t,H} = P_1 E_{A,H} + P_2 C_{ins} \quad (16)$$

It can be seen that the optimum insulation thickness for heating depends on the cost of energy and insulation material, as well as the properties of the wall and insulation material, COP of the cooling system, efficiency of the heating system, lifetime of the equipment, and discount and inflation rates.

As seen in Fig. 3, the outer wall of the building is an externally insulated wall consisting 2cm internal plaster, 13cm vertically perforated bricks, insulation materials and 3cm external plaster.

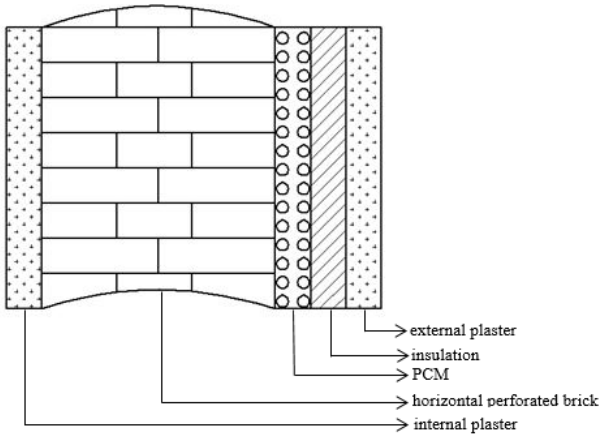

Fig. 3. A typical external wall section

The parameters and their values used in the calculation are given in Table I.

TABLE I. Parameters used in the calculation of insulation-thickness

Parameter	Value
Fuel	
Natural gas (for heating)	
Lower heating value(LHV)	34.526 x10^6
Cost, C_F	0.481 $/m^3
Efficiency, η_s	93 %
Coal	
Lower heating value(LHV)	29.295 x10^6
Cost, C_F	0.2216 $/m^3
Efficiency, η_s	65 %
Fuel oil	
Lower heating value(LHV)	40.594 x10^6
Cost, C_F	0.73 $/m^3
Efficiency, η_s	80 %
Insulation	
Expanded Polystyrene, EPS	
Conductivity, k	0.028 W/mK
Cost, C_I	133 $/m^3
External walls	
Resistance	R_{tw}=0.668 m^{2}K/W
Economic data	
Interest rate, i	%5
Inflation rate, d	%4
Lifetime, N	5 (PCM) 10 (without PCM)
Base temperature (for heating)	18°C

III. RESULTS

In this study, the optimum thickness calculations were made for a PCM sandwich wall using solar radiation heating loads in the following cities of Turkey; Antalya, Çorum and Kars located in the first, second and fourth degree-days region. Increasing the insulation thickness of buildings reduces heat loss and provides energy saving. The thickness of insulation can be increased if one desires to save more energy. Increasing insulation thickness reduces fuel costs as well as increases the insulation cost. However, the provided energy saving cannot meet the insulation cost after a certain threshold [12].

The curves of costs of insulation and fuel, and total cost versus the thickness of insulation on the heating load for Antalya are represented separately in Fig. 4. As shown, the optimum insulation thickness is 8mm for coal as fuel and the PCM wall. The same value is obtained as 24mm for without the PCM wall. This situation reduces the insulation cost approximately 1.6 times. The insulation thickness situated at the point of the minimum total cost gives us the optimum value.

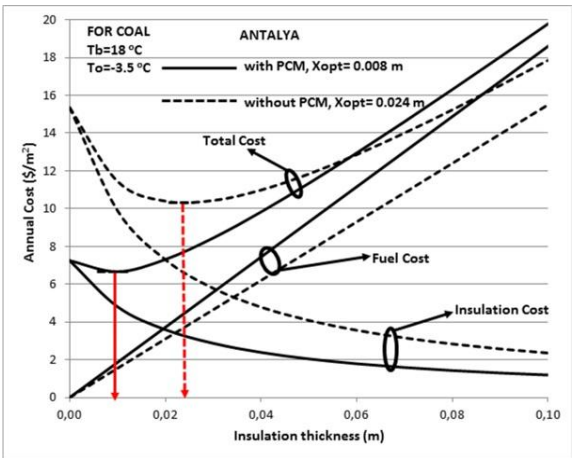

Fig.4. Effect of insulation-thickness on annual cost for Antalya

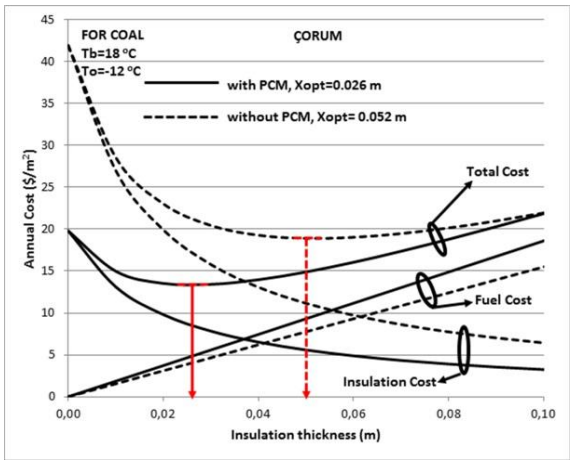

Fig.5. Effect of insulation-thickness on annual cost for Çorum

The heating degree-days value is 1083 for Antalya, whereas it is 2950 for Çorum. This means a 3 times increase in the heat demand of the building. As a result of the increase in heating degree-day value, the optimum insulation thickness is 26mm for PCM wall, and 52 mm for without PCM wall in the case of using coal as fuel (Fig.5). As shown, the 3 times increase in the value of heating degree-days decreases the effect of PCM on the optimum insulation thickness approximately 3.2 times. Thus, the change in the cost of insulation is increased to 2.1 times from 1.6 times. The cost of energy increases approximately 2.5 times according to the heating degree-days value.

The curves of costs of insulation and fuel, and total cost versus the thickness of insulation on the heating load for Kars are represented separately in Fig. 6. The heating degree-days value is obtained as 4776 for the city of Kars. The optimum insulation thickness is 38mm using coal as fuel and for PCM wall. The same value is obtained as 70mm for without PCM wall. As seen from Fig. 6, it increases the cost for isolation about 2 times. The base temperature is 18°C in the calculation of heating and cooling degree-hours. The optimum insulation thickness is calculated according to the base temperature.

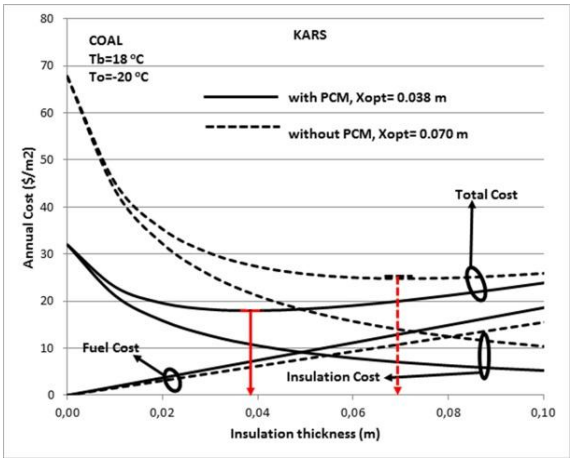

Fig.6. Effect of insulation-thickness on annual cost for Kars

As seen from Fig. 7, energy saving varies depending on the overall cost. Some undesired properties of PCM wall such as the long length of annual maintenance and labor costs and a limited life cycle of PCM depending on working cycle is reduced in the energy saving PCM wall compared to the wall without PCM. However, energy saving varies proportionally with the heating degree-days. Low solar irradiance and greater duration of the heating season increase the energy costs in cold climatic regions. Therefore, the necessity of proper insulation thickness is very important in terms of reducing energy costs in cold climatic regions. The heating degree-days values of cities vary depending on the climate condition, solar radiation and radiation time. The value of U required for the cooling load decreases while increasing the radiation time and amount of absorbing solar radiation. These situations increase the optimum thickness for hot regions [2].

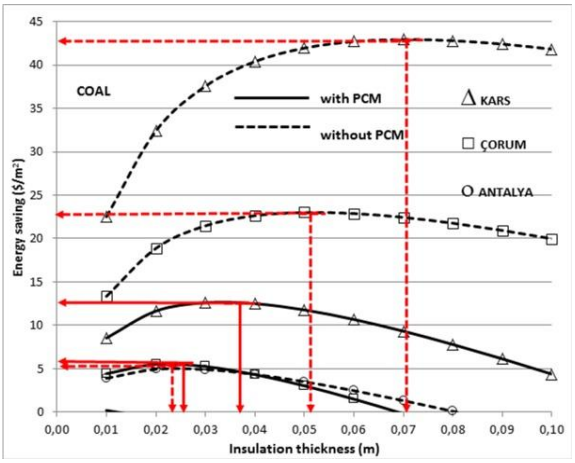

Fig.7. Effect of insulation-thickness on energy saving for selected cities

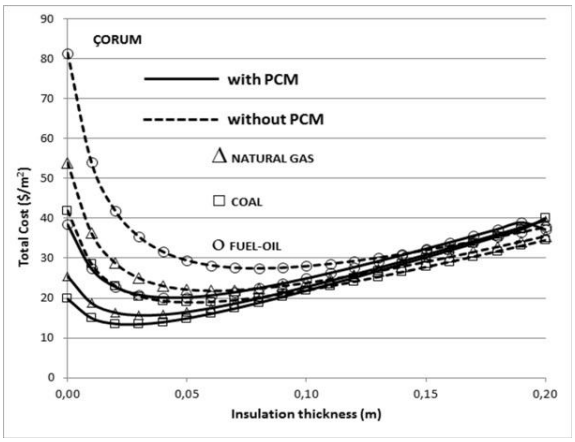

Fig.8. Effect of insulation-thickness on total cost for Çorum

The relationship between the insulation thickness and total cost according to fuel source and usage of PCM is shown in Fig 8. As the lower heating value of the fuel decreases, the total cost is significantly reduced depending on the type of fuel. The total cost becomes maximum when the insulation thickness is zero. The total cost decreases in the case of the insulation thickness increase until the optimum thickness, after the optimum insulation thickness, it increases again.

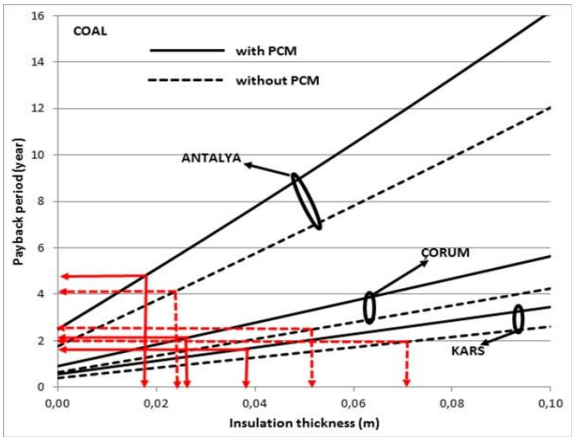

Fig.9. Effect of insulation-thickness on payback period for selected cities in case of using coal as fuel

Fig 9. displays the relationship between the insulation thickness and payback period according to using coal as fuel and usage of PCM for Antalya. Fig. 10 shows the effect of the fuel type. As can be seen from both figures, energy saving is less dependent on the installation and operating costs of PCM wall although the optimum insulation thickness is lower. At the same time, the payback period increases.

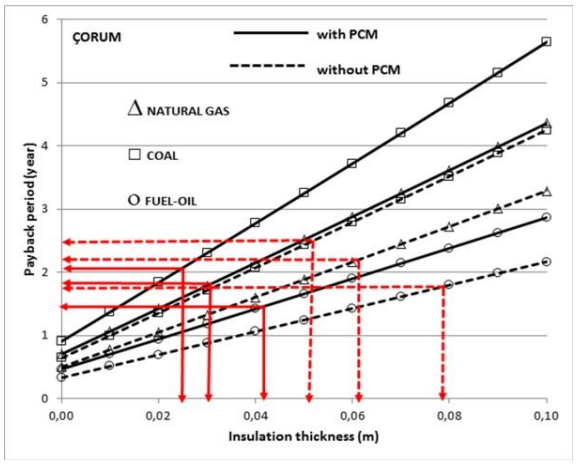

Fig.10. Effect of insulation-thickness on payback period for Çorum

IV. CONCLUSIONS

The present study was designed to determine the thermal characteristics and optimum insulation thickness of building external walls by using PCM for three different cities of Turkey. The optimum insulation thicknesses, annual costs, energy savings and payback periods were determined. In the calculations, LCCA is used. Insulation of buildings in Turkey with PCM is shown to be economically feasible and should be implemented, to save money and reduce imported energy.

REFERENCES

[1] A. Kürekçi, A.T. Bardakçı, H. Çubuk and Ö. Emanet, Determination of the optimum insulation thickness for all cities of Turkey, Plumbing Engineering, vol. 131, pp. 5-21, 2012.

[2] A. Bolattürk, Optimum Insulation Thickness for Buildings Walls With Respect to Cooling and Heating Degree-Hours in The Warmest Zone of Turkey, Building and Environment, vol. 43, pp. 1055-1064, 2008.

[3] MJ., Al-Khawaja, Determination and Selecting The Optimum Thickness of Insulation for Buildings in Hot Countries by Accounting for Solar Radiation, Applied Thermal Engineering, vol. 24, pp. 2601-2610.

[4] OA. Dombaycı, M. Gölcü, Y. Pancar, Optimization of insulation thickness for external walls using different energy-sources. Applied Energy, vol. 83, pp.921–8, 2006.

[5] M. Golcu, A. Dombaycı, S. Abalı, The Effect And Results Of The Optimum Insulation Thickness On Energy Saving For Denizli, J. Fac. Eng. Arch. Gazi Univ. , vol. 21, pp. 639- 644, 2006.

[6] K. Comaklı, B. Yuksel, Optimum Insulation thickness of External Walls for Energy Saving, Applied Thermal Engineering, vol. 23, pp. 473-479, 2003.

[7] A. Bolatturk, Determination of Optimum Insulation Thickness for Building Walls with Respect to Various Fuels and Climate Zones in Turkey, Applied Thermal Engineering, vol. 26, pp. 1301-1309, 2006.

[8] A. Ucar, F. Balo, Effect of Fuel Type on the Optimum Thickness of Selected Insulation Materials for the Four Different Climatic Regions of Turkey, Applied Energy, vol. 86, pp. 730-736, 2009.
[9] AE. Gurel, A. Daşdemir, Determination of optimum insulation thicknesses for heating and cooling loads in four different climatic regions of Turkey, Erciyes University Journal of the Institute of Science and Technology, vol. 27, pp. 346-352, 2011.
[10] A. Hasan, Optimizing Insulation Thickness for Buildings Using Life Cycle Cost, Applied Energy, vol. 63, pp.115-124, 1999.
[11] YA. Çengel, Heat Transfer: A Practical Approach 2th Ed., McGraw-Hill, 853, 1998.
[12] Bolattürk A, Dağıdır C , Güneş Radyasyonu Dikkate Alınarak Sıcak İklim ölgelerindeki Binalarda Optimum Yalıtım Kalınlığının Belirlenmesi**,** Isı Bilimi ve Tekniği Dergisi, 33, 1, 87-99, 2013.

[13] Duffie, J.A., Beckman, W.A., 1980, Solar Engineering Of Thermal Processes. A Wiley- Interscience Publication, 919p. Wisconsin.