INVESTIGATION OF PARAMETERS AFFECTING THE OPTIMUM THERMAL INSULATION THICKNESS FOR BUILDINGS IN HOT AND COLD CLIMATES

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This paper investigates the factors affecting the optimum insulation thickness and its payback period, such as heating and cooling energy requirements of building, lifetime, present worth factor, costs of insulation material and installation, costs of energy sources for heating and cooling, heating and cooling system efficiencies and solar radiation. For this purpose, by considering two cities characterizing the hot and cold climatic conditions, the optimum insulation thickness and its payback period have been calculated and a detailed parametric analysis has been carried out. To achieve practical results, the ranges of the parameters considered in the study include the values typically reported in the literature. The variations in the optimum insulation thickness and the payback period with all parameters are presented in graphical form. Finally, order of importance and contribution ratios of the examined parameters on the optimum insulation thickness are determined with the help of Taguchi method. It is found that HDD is the most efficient parameter on the optimum insulation thickness with an impact ratio of 27.33% of the total effect while the least efficient parameter is the efficiency of heating system with an impact ratio of 3.21%.

Key words*: optimization, thermal insulation thickness, energy conservation, life-cycle cost, Taguchi*

1. Introduction

The thermal insulation in building walls is one of the most valuable tools for reducing the energy consumption for space-heating and cooling in buildings. Determination of the economic thickness of the insulation in building walls has become the main aim of various studies [1-16,19-24]. The optimum thermal insulation thickness is a function of several factors, among which the climatic conditions appear to be one of the most important because it significantly affects the heating and cooling loads of a building. In the literature, there are numerous studies on the optimum thickness for thermal insulating materials to reduce the rate of heat flow to/from the buildings in hot/cold climates, such as Qatar, China, Turkey, Malaysia, Tunisia, Palestine, Maldives, Macedonia and Saudi Arabia [1-

5,16,23-28]. Al-Khawaja [1] calculated the optimum insulation thickness in buildings for used wallmate, fiberglass and polyethylene foam as a insulation material by considering the solar radiation in a hot country, Qatar. In this study, it was found that the wallmate insulation have the best performance for houses in Qatar. Yu et al. determined the optimum thickness of different insulation materials based on the heating degree-days (*HDD*s) and the cooling degree-days (*CDD*s) for a typical residential wall in China. By using the heating energy requirement, the optimum insulation thicknesses were calculated depends on the heating fuel types in Aytac and Aksoy [4], Dombayci et al. [5], Bolatturk [6], Comakli and Yuksel [7] for one or several cities in Turkey.

Daouas et al. [16] carried out the economic analysis of insulation thicknesses for different wall structures and insulation materials. In this study, it was found that expanded polystyrene is the most profitable insulation material for Tunisia. Moreover, it was concluded that the optimum thickness of insulation was 0.057 m, which leads to energy savings of 58% with a payback period of 3.11 years for expanded polystyrene insulation material and stone/brick sandwich wall. Kaynakli et al. [17] optimized the thermal insulation thickness used in the outer walls of buildings composing of different insulation applications having the same thermal resistance. They determined the minimum insulation thickness required to prevent condensation in building structural component. Bademlioglu et al. [18] examined the effect of water vapor diffusion resistance factor (VDRF) of insulation materials on condensation within constructions and investigated how the minimum insulation thickness required to prevent condensation changes with VDRF.

Taguchi Method is a statistical approach to use to determine the effect ratios of the parameters affecting the operating conditions. This statistical approach, which is generally used in the field of construction and manufacturing, has been used in recent years to optimize the performance of thermal systems. Verma and Murugesan [29] analyzed the performance of a solar assisted ground source heat pump using Taguchi technique. In the study, the design parameters were optimized to obtain solar collector area and ground heat exchanger length for space heating application with optimum COP. Arslanoglu and Yigit [30] examined the effect of lighting lamp radiation heat flux on human thermal comfort by using this method. Bademlioglu et al. [31] investigated the impact weights of parameters on ORC's first-law efficiency by utilizing Taguchi and ANOVA methods. In this study, the most efficient parameters on the thermal efficiency of the ORC (evaporator temperature, condenser temperature and turbine isentropic efficiency) were determined and the total effect ratios of these parameters were calculated to be 70%.

Unlike previous studies, in the present study, the optimum thermal insulation thicknesses for building walls have been determined based on the yearly transmission loads for two cities located in hot and cold climate conditions, and the parameters affecting the optimum thickness such as insulation materials, energy costs and geographical conditions (e.g. *HDD*, *CDD*) have been investigated. By considering the insulation installation cost in addition to the insulation material cost, the payback periods have also been calculated under different parameter conditions. In addition, a detailed study analyzing all these parameters and determining their contribution ratios on the optimum insulation thickness with statistical approach has not been encountered in the literature. For this reason, the major purpose of this study is to examine the parameters that present the most significant effect on the optimum insulation thickness and determine the importance level of these parameters by using Taguchi method.

2. Mathematical Model

2.1. Heating and cooling loads

One of the most widely used methods is the degree-days (*DD*s) [3,6,11,21,32]. The total number of *HDD*s and *CDD*s are obtained by:

$$HDD = \sum_{days}(T_b - T_o)^+ \tag{1}$$

$$CDD = \sum_{days}(T_o - T_b)^+ \tag{2}$$

where T_o is the daily mean outdoor air temperature and T_b is the base temperature. The plus sign on the outside of the parentheses states that only positive values are to be counted. In several studies [1-3], to consider the heat load from solar radiation on the heating and cooling energy requirements, the solar-air (sol-air) temperature was used instead of the outdoor air temperature for calculating the *HDD*s or *CDD*s. The $T_{sol\text{-}air}$ is given by [33]:

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

where h_o is the outer surface combined convection and radiation heat transfer coefficient, $\dot{q}_s$ is the solar radiation incident on the surface, α_s is the solar absorptivity of the surface, σ is the Stefan-Boltzmann constant, ε is the emissivity of the surface and T_{surr} is the sky and surrounding surface temperature.

The solar radiation incident on a surface depends on the surface gradient (slope) and the orientation. The surface slope and the orientation are expressed by the slope angle (β) and the azimuth angle (γ), respectively. For a vertical surface such as a building wall (β=90º), the incoming solar radiation calculation can be found from Duffie and Beckman [34] and Yigit and Atmaca [35]. The procedure was used in this study to calculate the incoming solar radiation on a vertical wall.

2.2. Economic analysis

The cost of insulation for an externall wall is a function of its thickness. The total insulation cost including the installation cost is given by:

$$C_{t,ins} = C_{ins}x + C_{inst} \tag{4}$$

Where C_{inst} is the installation cost (in US\$/m^2) and C_{ins} is the cost of insulation material per unit volume (in US\$/m^3). The C_H and C_C resulting from the transmission loads are given by:

$$C_H = \frac{86400 HDD C_f PWF}{(R_{t,w} + x/k) Hu \eta} \tag{5}$$

$$C_C = \frac{86400 CDD C_e PWF}{(R_{t,w} + x/k) COP} \tag{6}$$

Where C_f is the fuel cost, C_e is the electricity cost, *Hu* is lower heating value of the fuel and *PWF* is the present worth factor. The *PWF*, which based on the lifetime of the building or the insulation material (*LT*), the discount rate (*d*) and the inflation rate (*i*), is obtained as [12,23]:

$$PWF = \left(\frac{1+i}{d-i}\right)\left[1 - \left(\frac{1+i}{1+d}\right)^{LT}\right] \qquad (if\ d \neq i) \tag{7}$$

The total cost is the sum of the annual insulation costs (material and installation) and (heating and cooling) energy costs, which is expressed as:

$$C_t = \left(\frac{86400PWF}{R_{t,w}+x/k}\right)\left(\frac{C_f HDD}{Hu\eta} + \frac{C_e CDD}{COP}\right) + (C_{ins}x + C_{inst}) \quad (8)$$

The optimum insulation thickness is obtained by minimizing the total cost. When the derivative of the total cost equation with respect to the insulation thickness is set equal to zero, the optimum insulation thickness (x_{opt}) is obtained as follows:

$$x_{opt} = \left(\frac{86400PWF\{C_f HDD/(Hu\eta)+C_e CDD/COP\}k}{C_{ins}}\right)^{1/2} - R_{t,w}k \quad (9)$$

2.3. Taguchi Methodology

The Taguchi method, which was developed by Genichi Taguchi, is one of the most commonly used optimization technique to obtain best working condition and the order of importance of different factors for the objective function [36]. Despite the fact that, in the beginning, this method was used for experimental studies, it can be used for theoretical and numerical studies as well.

This optimization technique enables to optimize the system performance and determine the best options of parameters with less number of experiments or analyses rather than a full factorial analysis. A significant advantage of Taguchi method is reduction in time, cost and effort. Taguchi method contains certain orthogonal arrays tables to provide a comprehensive performance of full factorial analysis. The basic principles of the selection of appropriate orthogonal array type are presented in the statistical analysis section.

In this study, the Taguchi method is used for minimizing the total cost. At the beginning of the Taguchi analysis, the results of the objective function is converted to the S/N (signal to noise) ratio. Three types of performance characteristics are used for the calculating of the S/N ratio i.e., the lower is the better, the higher is the better and nominal is the best [37]. Because total cost is desired to be minimized in this study, the lower is the better performance characteristic is chosen. The S/N ratios for the lower is the better situation is calculated using the Eq. (10):

$$S/N = -10log\left(\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right) \quad (10)$$

where n indicates the number of case and y_i describes the result value for the ith performance characteristics.

3. Results and Discussions

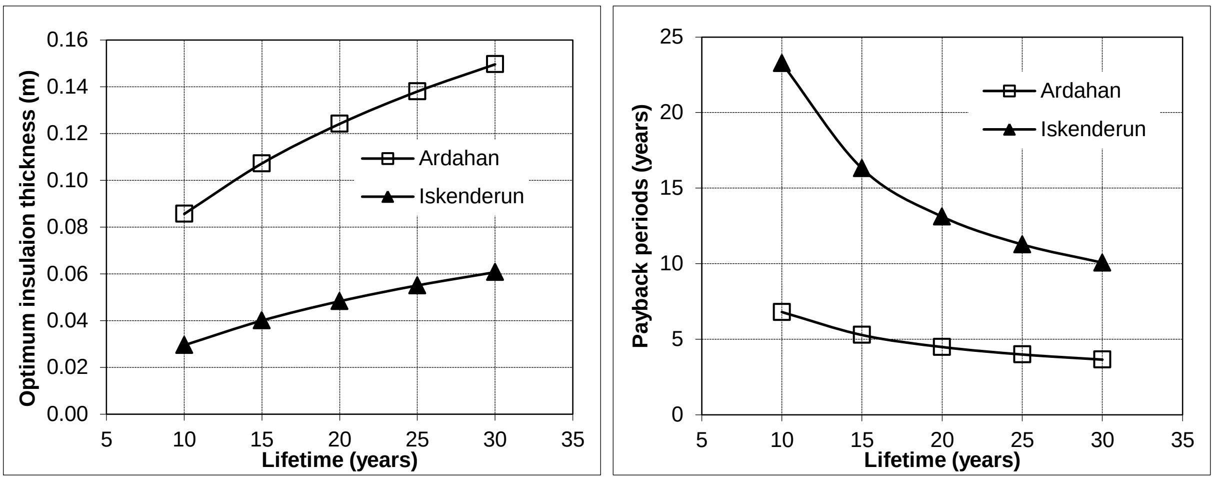
In this study, for the provinces of Iskenderun and Ardahan that are located in the first and fourth HDD regions, respectively, the above-mentioned approach was used to determine the optimum thermal insulation thickness for external walls.

The outdoor air temperature data used in the energy requirement calculations have to cover the long-term and depend on recent values. In this study, 10 year-ambient air temperature values have been used to determine the total heating and cooling *DD*s. According to these values, the total *HDD*s and *CDD*s have been computed, respectively, as 640 and 484 for Iskenderun, 5033 and 0 for Ardahan at the heating and cooling base temperatures of 18ºC and 24ºC. The certain parameters used in the calculations are shown in Table 1.

Table 1. Parameters used in the calculations.

Parameter	Value
External wall	
Total wall thermal resistance excluding the insulation layer, $R_{t,w}$	0.652 m^2K/W
Overall heat transfer coefficient, U	$1/(R_{ins}+0.652)$ W/m^2K
Insulation (polystyrene) [3-6,10]	
Conductivity, k	0.037 W/mK
Material cost, C_{ins}	150 US$/$m^3$
Installation cost, C_{inst}	7 US$/$m^2$
Fuel (natural gas)	
Price, C_f	0.4 US$/$m^3$
Lower heating value, LHV	34.526 x10^6 J/m^3
Efficiency of heating system, η	0.93
Electricity	
Price, C_e	0.13 US$/kWh
Coefficient of cooling system performance, COP	2.5 [3,14]
Financial parameters	
Inflation rate, i	3%
Discount rate, d	5%
Lifetime, LT	20
Present worth factor, PWF	16.4 (by Eq. 7)

The lifetime of the structure or the insulation material, which is one of the most important parameters in the economic evaluations, varies widely from 10 years to 30 years in the literature [1-5,14-16,27]. The effects of the *LT* on the optimum insulation thickness and the payback periods are presented in Fig. 1. The energy savings increases with an increasing insulation thickness, thus the payback period of the insulation decreases. When assuming a *LT* of 30 years, the payback period is found to be less than 4 years for Ardahan with an insulation thickness of 0.17 m, while it is approximately 10 years for Iskenderun with an insulation thickness of 0.071 m because the annual total energy requirement for Ardahan is higher.



(a) **(b)**

Fig. 1. The influences of the lifetime on (a) the optimum thermal insulation thickness and (b) the payback period.

*HDD*s and *CDD*s vary widely depending on the climatic conditions. The influences of heating and cooling *DD*s on the optimum insulation thickness and the payback period are presented in Fig. 2. As seen in Fig. 2, when the heating and cooling *DD*s increase, the thickness of the thermal insulation required increases, thus, the payback period of the insulation cost decreases. The optimum insulation thicknesses for Iskenderun are greater than those for Ardahan. The reason for this is that the *CDD* of Iskenderun is higher than that of Ardahan. In addition to this, the optimum insulation thicknesses for Ardahan are greater than those for Iskenderun because the *HDD* of Ardahan is higher than that of Iskenderun as shown in Fig. 2(c) and (d). Decreasing the payback period while increasing the *HDD* or *CDD* clearly shows that the application of insulation in hot or cold climates is more advantageous.

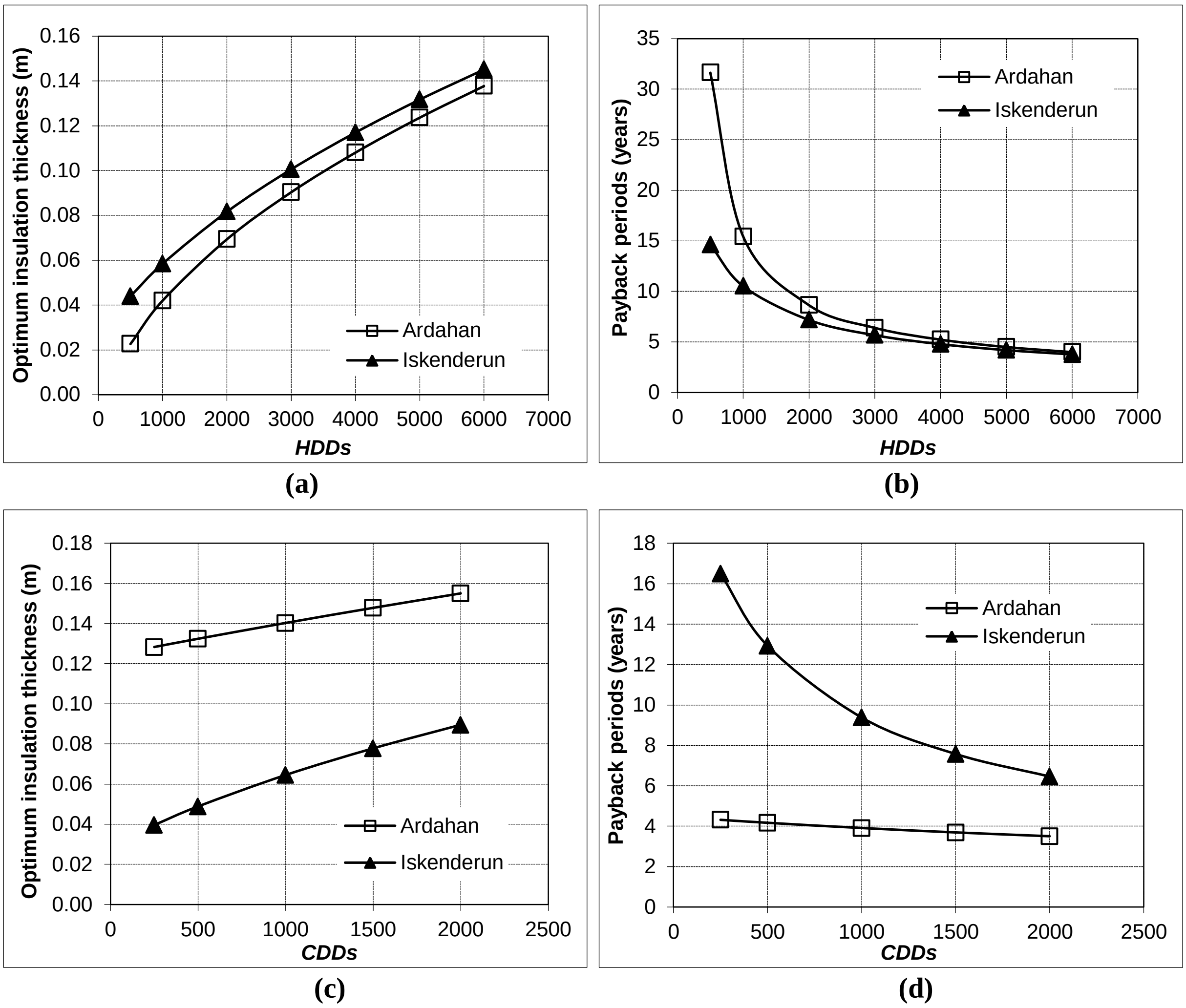


Fig. 2. The influences of *HDD* and *CDD* on the optimum thermal insulation thickness and the payback period.

The lifetime, inflation and discount rates affect the *PWF* value. Fig. 3 shows the effects of the *PWF* value on the optimum insulation thickness and the payback period. The *PWF* is used to obtain the present value of the yearly heating and cooling cost. Increasing the difference between *PWF* and *LT* values decreases the importance of the total energy cost over the lifetime. Hence, the thickness of insulation required decreases at low *PWF* values. When the *PWF* value is close to the *LT* value, the amount of savings in energy costs with insulation becomes more important compared to the insulation cost, and because of this, a thicker insulation can be used. Similar tendency and consequences were obtained by Al-Sanea and Zedan [25] and Daouas [10], which validate the results of the present investigation. Bolatturk [6], who investigated the effects of the *PWF* on the optimum insulation thickness with different fuel types based on only the heating energy requirement, found that the optimum insulation thickness increases with increasing *PWF*, which is in agreement with the present results.

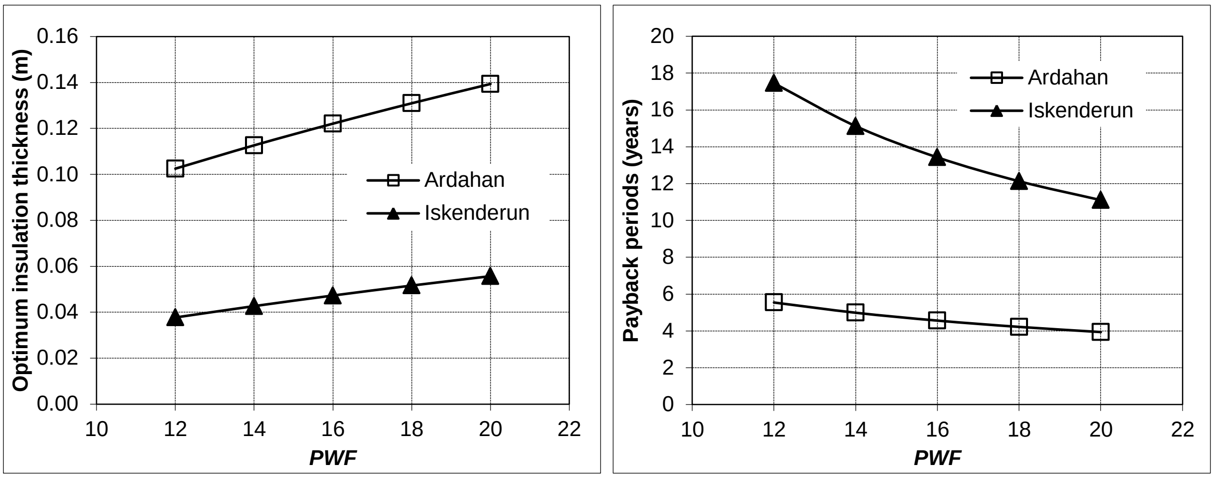


Fig. 3. The influences of *PWF* on (a) the optimum thermal insulation thickness and (b) the payback period.

According to literature [1-12,23-28], the insulation cost vary in a wide range of 24-215 US$/m^3 based on the material types. Fig. 4 shows the effect of the insulation material cost on the optimum insulation thickness and the payback period. When the insulation material cost increases, the total cost increases, and consequently, the optimum value of the insulation thickness decreases (Fig. 4a). Naturally, if the cost of the insulation material increases, the payback period of it increases. On the contrary, the insulation cost does not extremely affect the payback period for Ardahan compared to Iskenderun because there are higher annual (heating and cooling) energy requirements.

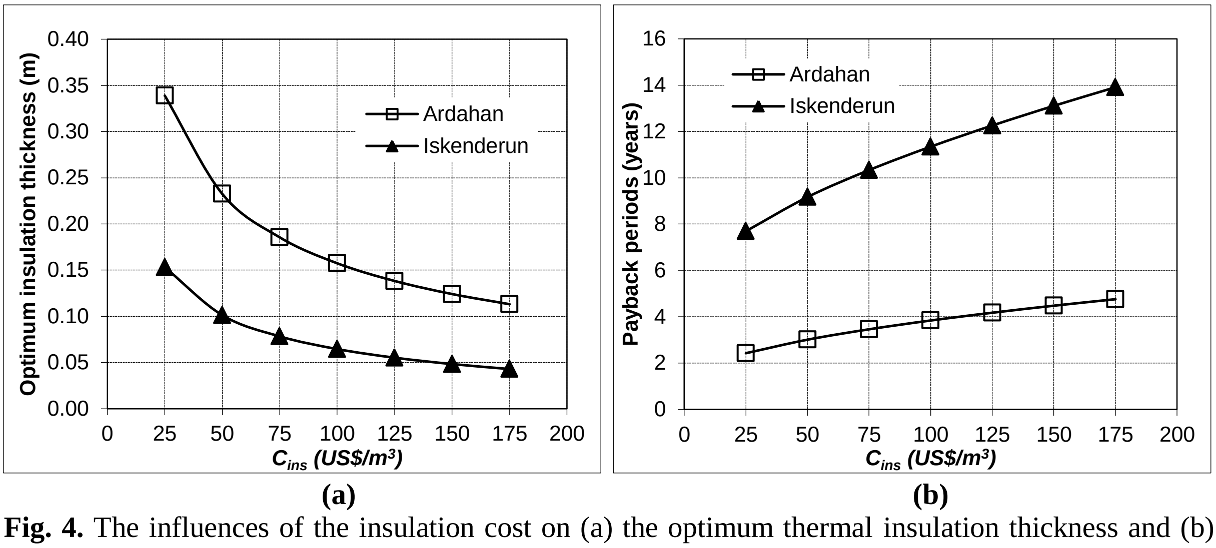
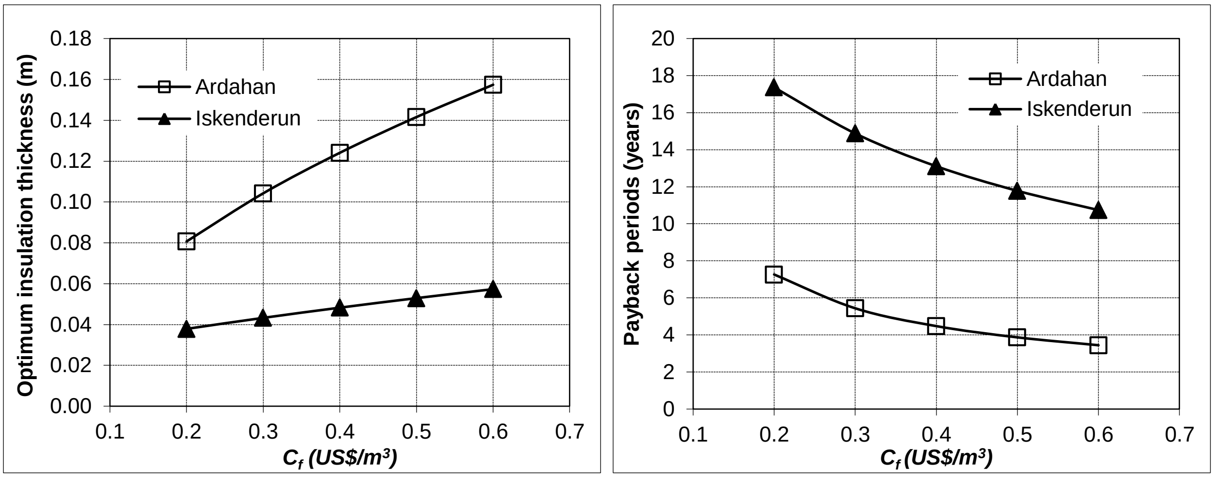


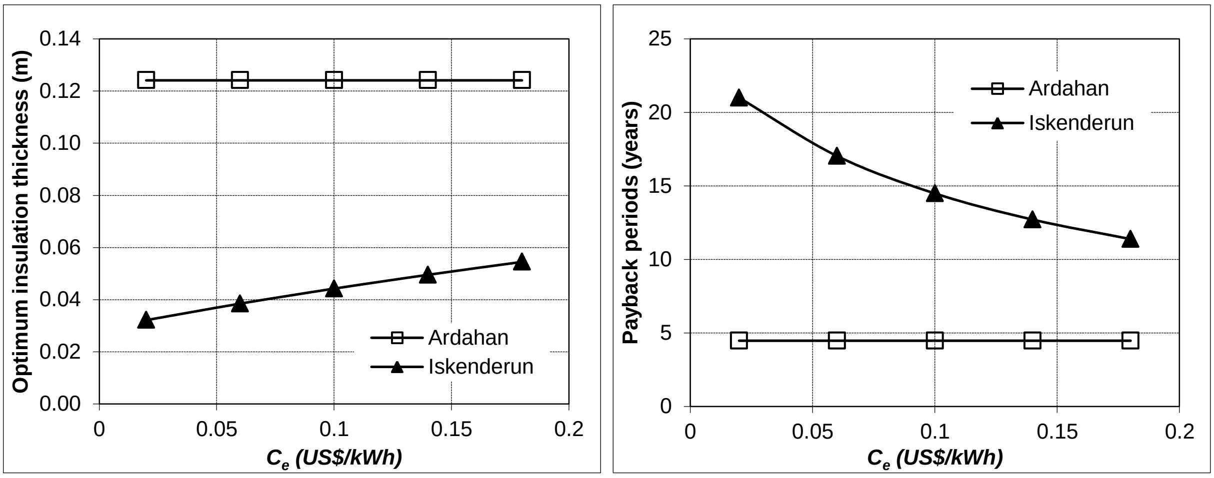
Fig. 4. The influences of the insulation cost on (a) the optimum thermal insulation thickness and (b) the payback period.

While Al-Sanea et al. [12] considered the electricity cost in the wide range of 0.013 – 0.107 US$/kWh (converted by 1 Saudi Riyal (SR) = 3.75 US$), the cost of natural gas varied in the range of 0.223-0.4103 US$/m^3 [5,22]. The effects of energy costs on the optimum insulation thickness and the payback period are shown in Figs. 5 and 6. To provide more economy, the optimum insulation thickness increases when increasing the unit of energy costs, and thus, the payback period decreases. The natural gas cost has a greater impact on the optimum insulation thickness for Ardahan because the heating energy requirement for Ardahan is higher than that for Iskenderun. However, the electricity cost does not affect the optimum insulation thickness for Ardahan because cooling is not required (*CDD* = 0).



(a) **(b)**

Fig. 5. The influences of the natural gas cost on (a) the optimum thermal insulation thickness and (b) the payback period.

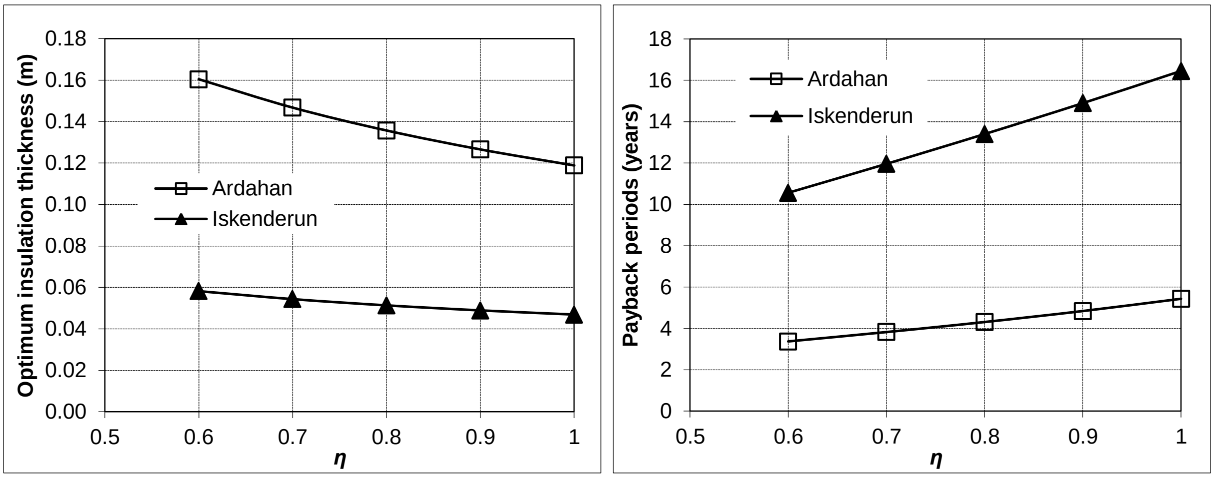


(a) **(b)**

Fig 6. The influences of the electricity cost on (a) the optimum thermal insulation thickness and (b) the payback period.

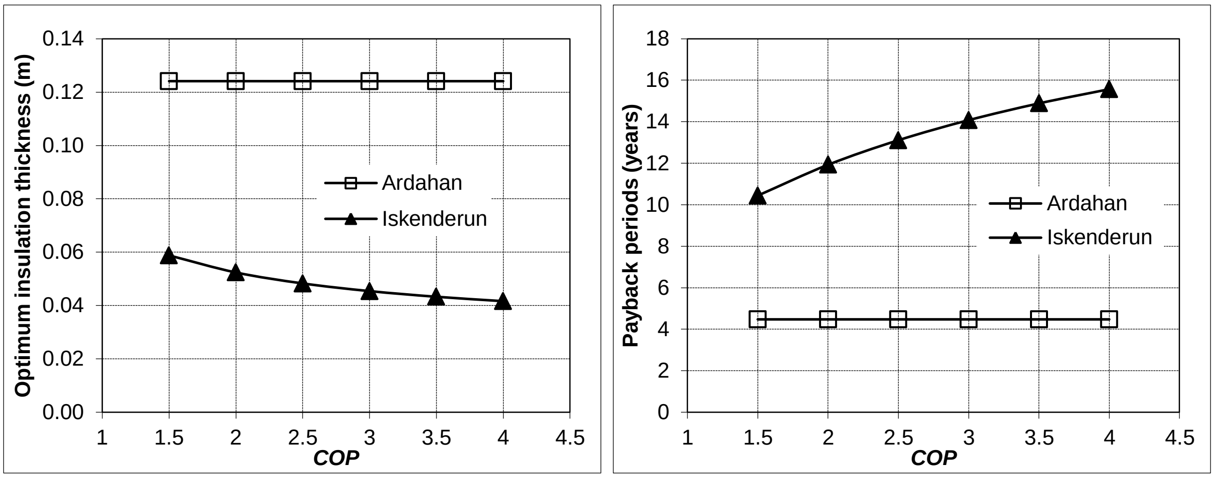
The most commonly used energy sources for heating in the literature are coal and natural gas. While the heating system efficiency was assumed to be 65-77% for coal, it was assumed to be 0.90-0.93% for natural gas [5,6,9,19,22]. On the other hand, the *COP* mainly based on the working conditions of the cooling system. On average, it was assumed to be between 2 and 3 [1-3,10,12,14].

Figs. 7 and 8 show the effects of the efficiency of the heating system and the *COP* of the cooling system. If the heating and cooling systems operate more efficiently by increasing the η and *COP* values, the heating and cooling costs of a building decrease. This situation leads to a reduction in the optimum insulation thickness. The optimum insulation thickness obtained for Ardahan is more greatly affected than that for Iskenderun by the variation in the η values because of the higher *HDDs*, as seen in Fig. 7a. On the other hand, the *COP* has no effect on the optimum insulation thickness for Ardahan because it affects only the cooling cost, as seen in Fig. 8a.



(a) **(b)**

Fig. 7. The influences of the efficiency of the heating system on (a) the optimum thermal insulation thickness and (b) the payback period.



(a) **(b)**

Fig. 8. The influences of the *COP* of a cooling system on (a) the optimum thermal insulation thickness and (b) the payback period.

3.1. Statistical Analysis

In this study, in addition to parametric analysis, Taguchi method was applied to find out the impact ratio of each parameter to insulation thickness. The control factors such as PWF, C_{ins}, C_f, C_e, $R_{t,w,}$ η, COP, *HDD* and *CDD* were chosen for the statistical analysis to find the importance level of these parameter on optimum insulation thickness. Parameter ranges (levels) chosen for statistical analysis were obtained by performing a literature review which is listed in Table 2.

Table 2. Parameters and levels used in analysis.

Parameters	Level 1	Level 2	Level 3
PWF	12	16	20
C_{ins} (US$/m^3)	250	180	120
C_f (US$/m^3)	0.2	0.4	0.6
C_e (US$/kWh)	0.02	0.1	0.18
$R_{t,w}$ (m^{2}K/W)	0.4	0.6	0.8
η	0.7	0.8	0.9
COP	2	3	4
HDD	1000	3000	5000
CDD	500	1000	1500

Table 3. The L27 orthogonal array.

Case	PWF	C_{ins}	C_f	C_e	$R_{t,w}$	η	COP	HDD	CDD
1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2
5	1	2	2	2	2	2	2	3	3
6	1	2	2	2	3	3	3	1	1
7	1	3	3	3	1	1	1	3	3
8	1	3	3	3	2	2	2	1	1
9	1	3	3	3	3	3	3	2	2
10	2	1	2	3	1	2	3	1	2
11	2	1	2	3	2	3	1	2	3
12	2	1	2	3	3	1	2	3	1
13	2	2	3	1	1	2	3	2	3
14	2	2	3	1	2	3	1	3	1
15	2	2	3	1	3	1	2	1	2
16	2	3	1	2	1	2	3	3	1
17	2	3	1	2	2	3	1	1	2
18	2	3	1	2	3	1	2	2	3
19	3	1	3	2	1	3	2	1	3
20	3	1	3	2	2	1	3	2	1
21	3	1	3	2	3	2	1	3	2
22	3	2	1	3	1	3	2	2	1
23	3	2	1	3	2	1	3	3	2
24	3	2	1	3	3	2	1	1	3
25	3	3	2	1	1	3	2	3	2
26	3	3	2	1	2	1	3	1	3
27	3	3	2	1	3	2	1	2	1

Selection the suitable orthogonal array type is the vital part of the Taguchi methodology. The suitable orthogonal array table can only be chosen after determining the total degree of freedom (DOF) which is the sum of the singular degree of freedom of each parameter. The number of each parameter levels minus 1 gives the individual DOF for the parameter. Since there are nine factors with three levels (see Table 2), the number of the total DOF is found to be 26. The DOF of the selected orthogonal array should not be lower than the total DOF according to the Taguchi method. Therefore, Taguchi orthogonal array of L27 (3^9) is established in this study as shown in Table 3.

Signal to noise (S/N) ratios are obtained for every case and average S/N ratios for the optimum insulation thickness, the rank of significance, contribution ratios of all factors are shown in Table 4.

Table 4. The rank of significance and contribution ratio for optimum insulation thickness.

Parameters									
Level	PWF	C_{ins}	C_f	C_e	$R_{t,w}$	η	COP	HDD	CDD
1	23.39	24.46	22.42	22.57	21.2	21.62	20.78	25.36	22.55
2	21.35	21.63	21.76	21.64	21.5	21.2	21.86	20.8	21.56
3	20.06	18.65	20.63	20.59	22.1	21.99	22.18	18.65	20.69
Delta	3.32	5.81	1.79	1.98	0.89	0.79	1.4	6.71	1.85
Rank	3	2	6	4	8	9	7	1	5
Contribution Ratios (%)	13.52	23.66	7.29	8.06	3.62	3.21	5.7	27.33	7.57

It is seen that HDD is the most efficient parameter on optimum insulation thickness with an impact ratio of 27.33% of the total effect while the least efficient parameter is the efficiency of heating system (η) with an impact ratio of 3.21%. It can be observed that HDD, C_{ins} and PWF have a large impact on the optimum insulation thickness, compared with the other parameters. These three parameters represent to account for 65% of the total effect of the parameters. This result is in a good agreement with Arslanoglu and Yigit [20]. They examined the influences of only five parameters on the optimum insulation thickness, and found that the most and the least effective parameters are HDD and wall type, respectively. In addition, the efficiency of heating system was not considered in their optimization. In our study, basic results are convenient with these results.

4. Conclusions

There are many factors affecting the optimum thermal insulation thickness in building walls, such as the heating and cooling *DD*s, the lifetime, the present worth factor, the costs of the insulation material and installation, the costs of energy sources for heating and cooling, the heating and cooling system efficiencies (η and *COP*). In this study, the effects of these factors for hot and cold climates on the optimum insulation thickness and its payback period have been investigated. For this purpose, the two cities in Turkey, Iskenderun and Ardahan, located in the first and fourth zones, which characterize the hot and cold climates respectively, have been considered. The total *HDD*s and *CDD*s have been calculated, respectively, as 640 and 484 for Iskenderun, 5033 and 0 for Ardahan according to 10 year-ambient air temperature measurements. On the basis of these *DD*s, the parametric analysis is carried out. Furthermore, effective factors have been examined in terms of the order of importance using Taguchi method.

The results of the parametric analysis showed that the optimum insulation thickness for external walls increased with increasing heating/cooling energy requirements (*HDD*s and *CDD*s), lifetime, *PWF*, natural gas and electricity costs. However, it decreased with increasing insulation material cost, heating and cooling system efficiencies.

The most effective parameters on optimum insulation thickness were found to be the heating *DD*s (27.33%), the insulation cost (23.66%), PWF (13.52%) and the electricity cost (8.06%), while the less effective parameters were found to be the efficiency of heating system (3.21%), the wall thermal resistance (3.62%), COP (5.7%), the fuel cost (7.29%), and the cooling *DD*s (7.57%). The insulation cost has a greater effect on the payback period for lower annual (heating + cooling) transmission loads (i.e., for moderate climates).

Nomenclature

C	– cost, [US$]
CDD	– cooling degree-days
COP	– coefficient of performance
DOF	– degree of freedom
d	– discount rate
HDD	– heating degree-days
h_o	– combined convection and radiation heat transfer coefficient, [W/m^2°C]
i	– inflation rate
k	– thermal conductivity of insulation material, [W/m°C]
LHV	– lower heating value, [J/m^3]
LT	– lifetime, [year]
PWF	– present worth factor
$\dot{q}_s$	– solar radiation incident on a surface, [W/m^2]
$R_{t,w}$	– total wall thermal resistances excluding the insulation layer, [m^2°C/W]
T	– temperature, [°C]
U	– overall heat transfer coefficient of wall, [W/m^2°C]
x	– thermal insulation thickness, [m]

Subscript

b	– base
C	– cooling
e	– electricity
f	– natural gas
H	– heating
ins	– insulation material
inst	– insulation installation
o	– outdoor
opt	– optimum

Greek Symbols

ε	– emissivity of a surface
β	– slope angle
γ	– azimuth angle
σ	– Stefan-Boltzmann constant, [W/m^2°C^4]
δ	– declination angle
θ	– angle of incidence of the solar radiation
ω	– hour angle
η	– efficiency of the heating system

References

[1] Al-Khawaja, M. J., Determination and selecting the optimum thickness of insulation for buildings in hot countries by accounting for solar radiation, *Applied Thermal Engineering*, *24* (2004), pp. 2601-2610

[2] Yu, J., *et. al.*, A study on optimum insulation thicknesses of external walls in hot summer and cold winter zone of China, *Applied Energy*, *86* (2009), pp. 2520-2529

[3] Bolatturk, A., Optimum insulation thicknesses for building walls with respect to cooling and heating degree-hours in the warmest zone of Turkey, *Building and Environment, 43* (2008), pp. 1055-1064
[4] Aytac, A. and Aksoy, U. T., The relation between optimum insulation thickness and heating cost on external walls for energy saving (*in Turkish*), *J Faculty Eng Architecture of Gazi University, 21* (2006), pp. 753-758
[5] Dombayci, O. A., *et. al.*, Optimization of insulation thickness for external walls using different energy-sources, *Applied Energy, 83* (2006), pp. 921-928
[6] Bolatturk, A., Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey, *Applied Thermal Engineering*, *26* (2006), pp. 1301-1309
[7] Comakli, K. and Yuksel, B., Optimum insulation thickness of external walls for energy saving, *Applied Thermal Engineering, 23* (2003), pp. 473-479
[8] Canbolat, A. S., *et. al.*, Determination of proper insulation thickness for building walls regarding economic consideration, *International Research Journal of Advanced Engineering and Science*, *4* (2018), pp. 173-176
[9] Ucar, A. and Balo, F., Determination of the energy savings and the optimum insulation thickness in the four different insulated exterior walls, *Renewable Energy, 35* (2010), pp. 88-94
[10] Daouas, N., A study on optimum insulation thickness in walls and energy savings in Tunisian buildings based on analytical calculation of cooling and heating transmission loads, *Applied Energy, 88* (2011), pp. 156-164
[11] Ozel, M. and Pihtili, K., Determination of optimum insulation thickness by using heating and cooling degree-day values (*in Turkish*), *J Eng Natural Sci, 26* (2008), pp. 191-197
[12] Al-Sanea, S. A., *et. al.*, Heat transfer characteristics and optimum insulation thickness for cavity walls, *J Thermal Envelope Build*, *26* (2003), pp. 285-307
[13] Ozel, M. and Pihtili, K., Investigation of the most suitable location of insulation applying on building roof from maximum load levelling point of view, *Building and Environment, 42* (2007), pp. 2360-2368
[14] Soylemez, M. S. and Unsal, M., Optimum insulation thickness for refrigeration applications, *Energy Conversion and Management, 40* (1999), pp. 13-21
[15] Lollini, B. and Fasano, M., Optimisation of opaque components of the building envelope. Energy, economic and environmental issues, *Building and Environment, 41* (2006), pp. 1001-1013
[16] Daouas, N., *et. al.*, Analytical periodic solution for the study of thermal performance and optimum insulation thickness of building walls in Tunisia, *Applied Thermal Engineering*, *30* (2010), pp. 319-326
[17] Kaynakli, O., *et. al.*, Determination of optimum insulation thickness for different insulation applications considering condensation, *Tehnicki Vjesnik*, *25* (2018), pp. 32-42
[18] Bademlioglu, A. H., *et. al.*, The effect of water vapor diffusion resistance factor of insulation materials for outer walls on condensation, *Journal of Thermal Science and Technology, 38* (2018), pp. 15-23
[19] Ucar, A., *et. al.*, Application of three different methods for determination of optimum insulation thickness in external walls, *Environmental Progress & Sustainable Energy, 30* (2011), pp. 709-719
[20] Arslanoglu, N. and Yigit, A., Investigation of efficient parameters on optimum insulation thickness based on theoretical-taguchi combined method, *Environmental Progress & Sustainable Energy*, *36* (2017), pp. 1824-1831
[21] Sisman, N., *et. al.*, Determination of optimum insulation thicknesses of the external walls and roof (ceiling) for Turkey's different degree-day regions, *Energy Policy, 35* (2007), pp. 5151-5155
[22] Ozkan, D. B. and Onan, C., Optimization of insulation thickness for different glazing areas in buildings for various climatic regions in Turkey, *Applied Energy, 88* (2011), pp. 1331-1342
[23] Hasan, A., Optimizing insulation thickness for buildings using life cycle cost, *Applied Energy, 63* (1999), pp. 115-124
[24] Gurel, A. E. and Dasdemir, A., Economical and environmental effects of thermal insulation thickness in four climatic regions of Turkey, *International Journal of Renewable Energy Research*, *1* (2011), pp. 1-10

[25] Al-Sanea, S. A. and Zedan, M. F., Effect of insulation location on thermal performance of building walls under steady periodic conditions, *International Journal of Ambient Energy, 22* (2001), pp. 59-72
[26] Dedinec, A., *et. al.*, Optimization of heat saving in buildings using unsteady heat transfer model, *Thermal Science*, *19* (2015), pp. 881-892
[27] Mahlia, T. M. I. and Iqbal, A., Cost benefits analysis and emission reductions of optimum thickness and air gaps for selected insulation materials for building walls in Maldives, *Energy, 35* (2010), pp. 2242-2250
[28] Dombayci, O. A., The environmental impact of optimum insulation thickness for external walls of buildings, *Building and Environment 42* (2007), pp. 3855-3859
[29] Verma, V. and Murugesan, K., Optimization of solar assisted ground source heat pump system for space heating application by Taguchi method and utility concept, *Energy and Buildings*, *82* (2014), pp. 296-309
[30] Arslanoglu, N. and Yigit, A., Experimental investigation of radiation effect on human thermal comfort by Taguchi method, *Applied Thermal Engineering, 92* (2016), pp. 18-23
[31] Bademlioglu, A. H., *et. al.*, Investigation of parameters affecting Organic Rankine Cycle efficiency by using Taguchi and ANOVA methods, *Applied Thermal Engineering, 145* (2018), pp. 221-228
[32] Papakostas, K., *et. al.*, Impact of the ambient temperature rise on the energy consumption for heating and cooling in residential buildings of Greece, *Renewable Energy, 35* (2010), pp. 1376-1379
[33] Cengel, Y. A., *Heat transfer: A practical approach*, McGraw-Hill Inc., New York, USA, 1998
[34] Duffie, J. A. and Beckman, W. A., *Solar engineering of thermal processes*, Wiley, New York, USA, 1991
[35] Yigit, A. and Atmaca, I., *Solar energy (in Turkish)*, Alfa-Aktuel, Bursa, Turkey, 2010
[36] Taguchi, G., *Taguchi Techniques for Quality Engineering*, Quality Resources, New York, USA, 1987.
[37] Ross, P. J., *Taguchi Techniques for Quality Engineering*, second ed., McGraw-Hill Inc., New York, USA, 1996.

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