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The determination of optimum thermal insulation thickness for external walls of laying hen houses

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ABSTRACT
One of the main objectives of the energy strategy of any country is conservation. Thermal insulation is of utmost importance in the context of energy conservation. Therefore, this study aims to optimize insulation layer for the ten cities of Turkey which have the highest number of laying hens. The yearly heating and cooling loads were determined by using degree day method. Then optimum insulation thickness, energy savings, payback periods and CO_2 emission were computed for Rock wool (RW) and Glass wool (GW) insulation materials. Results indicated that the optimum thickness of insulation for RW insulation material varies between 0.046 and 0.159 m, energy savings range between 35.42% and 74.56%, and payback periods were between 0.67 and 2.00 years, while for GW insulation material optimum insulation thickness varies from 0.045 and 0.150 m, energy savings vary in the range of 42.17% and 77.72%, and payback periods were between 0.61 and 1.72 years depending on the city, and type of fuel. The lowest CO_2 emission reductions (64.79%) were obtained for İzmir with natural gas and RW insulation material are used, while the highest value (88.76%) was achieved for Kayseri with LPG and GW insulation.

Keywords:
Energy conservation
Emission
Insulation
Laying hens

Yumurta tavuğu kümeslerinin dış duvarları için optimum yalıtım kalınlığının belirlenmesi

ÖZET
Bir ülkenin enerji stratejisinin temel hedeflerinden biri de enerji tasarrufudur. Isı yalıtımı enerjinin korunumun da önemli bir yere sahiptir. Bu nedenle, bu çalışma da Türkiye'de en fazla yumurta tavuğu yetiştiren on il için optimum yalıtım kalınlığının belirlenmesi amaçlanmıştır. Derece gün yöntemi kullanılarak yıllık ısıtma ve soğutma yükleri belirlendikten sonra taş yünü (RW) ve cam yünü (GW) yalıtım malzemeleri için optimum yalıtım kalınlığı, enerji tasarrufu, geri ödeme süreleri ve CO_2 emisyonları hesaplanmıştır. Sonuç olarak şehir ve yakıt türüne bağlı olarak RW yalıtım malzemesi için optimum yalıtım kalınlığının 0.046 ile 0.165 m arasında, enerji tasarrufunun %35.42 ile %74.56 arasında ve geri ödeme süresinin 0.67 ile 2.00 yıl arasında olduğu, GW yalıtım malzemesi içinse optimum yalıtım kalınlığının 0.045 ile 0.150 m arasında, enerji tasarrufunun %42.17 ile %77.72 arasında ve geri ödeme süresinin 0.61 ile 1.72 yıl arasında değiştiği belirlenmiştir. CO_2 emisyonundaki en düşük azalma oranı (%64.79) İzmir ili için doğalgaz ve RW yalıtım malzemesi kullanıldığı zaman, en yüksek azalma oranı ise (%88.76) LPG ve GW yalıtım malzemesi ile Kayseri'de elde edilmiştir.

Anahtar Sözcükler:
Enerjinin korunumu
Emisyon
Yalıtım
Yumurta tavukları

1. Introduction

The concept of 'energy conservation' is a critical issue worldwide, due to global energy resources nearing exhaustion and rising energy costs (Petrecca, 2014). Faced with reports about the exploitation of energy resources, some national governments focused on resource conservation and sustainability. Various policies to decrease energy demand have been implemented. A common strategy for reducing energy demand in buildings is to enhance the thermal insulation of their envelopes. Implementing insulation not only improves the energy efficiency of a building, it also improves the quality of the indoor environment (Anastaselos et al., 2017).

Energy savings increased with the increasing insulation thickness. However, the cost of insulation investment will increase linearly with the thickness of insulation material (Ozel, 2011). Thus, the economic analysis should be considered in determining the ideal insulation thickness.

The costs of insulation and fuel are the two important parameters that affect the total cost of heating and cooling in insulated buildings. As the thickness of insulation increases, heat loss reduces and energy savings increase accordingly (Zhu et al., 2011). The fuel costs decrease as heat losses are reduced. On the other hand, increasing insulation thickness results in an increase in initial investment costs. However, the price of the fuel and insulation is lowered until a certain thickness insulation value is achieved and then its again increased. The minimum point of the cost curve is the optimal thickness value of the insulation.

Despite the existence of various studies on the ideal insulation thickness material in residential buildings for many different countries (Ashouri et al., 2016; Barrau et al., 2014; Bolattürk, 2008; Daouas, 2011; Gelegenis and Axaopoulos, 2017; Liu et al., 2015; Ramin et al., 2016; Vincelas and Ghislain, 2017; Yu et al., 2009; Yuan et al., 2016; Zhu et al., 2011), to date there are no comprehensive studies on calculation of optimum insulation thickness in livestock buildings. Livestock buildings theoretically provide protection from adverse climatic conditions depending on housing quality (Legrand et al., 2009). Therefore, proper design of buildings using insulation materials in agricultural industry is inevitable for maximizing energy savings. The most important need of livestock buildings is to prevent undesirable temperature transmission which can affect animal performance and health during the harsh summer and winter periods. In livestock buildings, most of the energy is used for heating in colder regions, and for cooling in warmer regions.

Poultry, the leading agricultural sector in Turkey, has achieved considerable progress and great economic contribution. With approximately 1,900 million tons annually as the world's 8^{th} biggest poultry producer (USDA, 2016), Turkey aims to be the world's leading poultry industry in the next decade. To accomplish this goal, poultry houses should be designed as an environment in which flocks can be maximized while the total production costs minimized. Thermal insulation is one of the most efficient ways to reduce total costs in buildings. The implementation of insulation not only helps to reduce fuel costs, but also to ensure bird health and well-being.

Social concerns about animal comfort and welfare have been increasing considerably over the last few decades in many European countries and beyond, which have created global awareness (Blokhuis et al., 2013). Temperature is one of the main parameters that affect animal comfort and welfare. Birds can retain over a wide range of ambient temperatures in their body like homoeothermic animals. For laying hens, the most comfortable temperature is 18-24 °C (Holik, 2009). Temperature above these ranges reduces appetite and increases the rate of mortality in a flock. Therefore, buildings have to be designed and managed to ensure a comfortable temperature.

Based on the above, the goal of this work is to determine optimum insulation thickness and then calculate the energy savings, payback periods, and CO_2 emissions resulting from use of insulation for hen houses. To achieve this objective, ten cities in Turkey with the highest number of laying hens are selected and analyzed.

2. Materials and Methods

2.1. The structure of building wall

In this study, the hollow brick, a construction material widely used in poultry buildings, was selected as building material. The insulated composite wall (from inside to outside) comprises a 2 cm lime based plaster, 19 cm hollow brick, 3 cm cement-based plaster and insulation layer placed on external surface as shown in Figure 1. For all selected cities, this wall structure was used for calculation. Two insulation materials, Rock wool (RW) and Glass wool (GW), were selected to determine optimum insulation thickness since they are the most cost-effective materials.

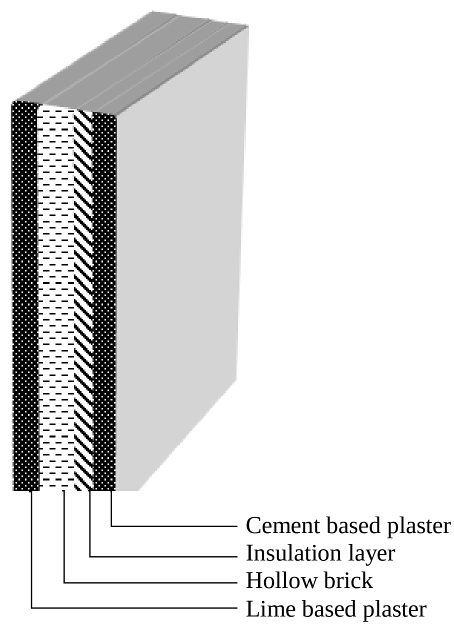

Figure 1. The wall structure

2.2. Degree days method

Many energy analysis techniques can be used for estimating energy requirements, however, the degree days (DDs) method is the one of the most practical and well-known method (Indraganti and Boussaa, 2017; Roshan et al., 2017). The calculation of DDs is based on reference temperature. If the outdoor temperature is higher than reference temperature, there is a cooling requirement of environment and if outdoor temperature is lower than reference temperature, there is a heating requirement of environment. The measurement of heating degree days (HDD) and cooling degree days (CDD) plays an important role in determining the thermal needs of building in different locations and assessing the annual energy demands. To determine the annual HDD and CDD of selected cities, base temperature was taken 18 °C for heating and 24 °C for cooling (Holik, 2009).

The heat transfer process through a unit area of external wall is computed as follows,

$$q = U \times \Delta T \quad (1)$$

where U is the coefficient of total heat transfer (W m^{-2} K^{-1}), ΔT is difference between average daily temperature and reference temperature. The annual heat loss or gain in unit area (W m^{-2}) is determined with Eq. (2) and Eq. (3).

$$q_H = 86400 \times HDD \times U \quad (2)$$

$$q_C = 86400 \times CDD \times U \quad (3)$$

The annual amount of energy required for heating and cooling is calculated by the following equations (Kurekci, 2016).

$$E_{AH} = \frac{86400 \times HDD \times U}{n_s} \quad (4)$$

$$E_{AC} = \frac{86400 \times CDD \times U}{COP} \quad (5)$$

where η_s is combustion system efficiency, COP is cooling system performance.

2.3. Optimum insulation thickness

Life-cycle cost analysis (LCCA) is used to evaluate investments by comparing all their initial and future expected benefits with all their initial and future expected costs. By determining present worth factor (*PWF*) and lifetime (*N*), annual energy cost calculated. The *PWF* is calculated based on interest rate (*i*) and inflation rate (*g*) as follows.

The interest rate adjusted for inflation rate *r* is given by (Hasan, 1999).

$$r = \begin{cases} \dfrac{i - g}{1+g}; & i > g \\ \dfrac{g - i}{1+i}; & i < g \end{cases} \quad (6)$$

$$PWF = \frac{(1+r)^N - 1}{r(1+r)^N} \quad (7)$$

where N is the lifetime assumed to be 20 years (Mahlia and Iqbal, 2010; Mahlia et al., 2007; Yu et al., 2009).

Annual heating and cooling fuel cost for unit surface can be determined from the following equations,

$$C_{AH} = \frac{86400 \times HDD \times C_f}{(R_{wt} + R_{ins}) \times H_u \times n_s} \quad (8)$$

$$C_{AC} = \frac{86400 \times CDD \times C_e}{(R_{wt} + R_{ins}) \times COP} \quad (9)$$

where C_f is the fuel price, C_e is the electricity price, R_w is total heat resistance of the wall with non-insulation (m^2 K W^{-1}), R_{ins} is the heat resistance of the insulation layer (m^2 K W^{-1}), and H_u is the lower heating values of fuels.

The cost of insulation is calculated as:

$$C_{ins} = C_I \times d \quad (10)$$

where C_I and d is the insulation cost and thickness, respectively.

The total cost of insulated building is given as,

$$C_{THC} = (C_{AH} \times PWF + C_{ins}) + (C_{AC} \times PWF + C_{ins}) \quad (11)$$

The optimum insulation thickness for heating and cooling is calculated as follows,

$$d_{opt,H} = 293.94 \times \left(\frac{HDD \times C_f \times PWF \times k}{C_I \times n_s \times H_u} \right)^{1/2} - k \times R_{wt} \quad (12)$$

$$d_{opt,C} = 293.94 \times \left(\frac{CDD \times C_e \times PWF \times k}{C_I \times COP} \right)^{1/2} - k \times R_{wt} \quad (13)$$

The optimum insulation thickness can be calculated,

$$d_{opt,HC} = 293.94 \times \left[\left(\frac{HDD \times C_f \times PWF \times k}{C_I \times n_s \times H_u} \right) + \left(\frac{CDD \times C_e \times PWF \times k}{C_I \times COP} \right) \right]^{1/2} - k \times R_{wt} \quad (14)$$

Annual total net saving amount for buildings is found
by:

$$A_{year,HC} = C_{pre} - C_{THC} \tag{15}$$

where k is is the thermal conductivity of the insulation and C_{pre} is the pre-insulation heating-cooling cost.

Payback period can be calculated as follows,

$$PP_{H,C} = \frac{C_{ins}}{A_{year,HC}} \tag{16}$$

2.4. Optimum insulation thickness

An increase in the thickness of the insulation decreases heat loss in houses and also reduces the fuel consumption and air pollution.

The general equation of combustion for fuel can be written as;

$$C_a H_b O_d S_e N_f + \varepsilon X (O_2 + 3.76 N_2) \rightarrow aCO_2 + \left(\frac{b}{2}\right) H_2O + (\varepsilon - 1) XO_2 + eSO_2 + YN_2 \tag{17}$$

The constants X and Y are defined as:

$$X = \left(a + \frac{b}{4} + e - \frac{d}{2}\right) \tag{18}$$

$$Y = \left(3.76 \varepsilon X + \frac{f}{2}\right) \tag{19}$$

The total CO_2 emission (kg CO_2 year^{-1}) from burning a fuel can be calculated as:

$$M_{CO_2} = \frac{44a}{M} \times M_f \tag{20}$$

where, M_f is yearly total burned fuel (kg year^{-1}) and M is molecular weight of the fuel (kg kmol^{-1}) can be written as follows,

$$M = 12a + b + 16d + 32e + 14f \tag{21}$$

$$M_f = \frac{86400 \times HDD}{(R_{wt} + R_{ins}) \times n_s \times H_u} \tag{22}$$

2.5. Analysis

The cities in Turkey with the highest number of laying hens and their degree days are calculated and presented in Table 1.

Table 1. Degree day values of selected cities in Turkey

City	Number of laying hens	Elevation (m)	Latitude	Longitude	HDD	CDD
Afyon	18469	1033.74	38.75	30.53	3448	137
Konya	11557	1028.59	37.87	32.48	3506	176
Balıkesir	6621	147.00	39.65	27.87	2641	241
İzmir	5647	28.55	38.43	27.17	1781	429
Ankara	4530	890.52	39.95	32.88	3303	170
Bursa	4450	100.32	40.23	29.02	2602	212
Manisa	4315	71.00	36.62	27.43	2197	487
Çorum	4229	775.91	40.55	34.95	3564	135
Kayseri	3727	1093.00	38.75	35.48	3681	162
Gaziantep	2889	854.00	37.05	37.35	2647	475

The optimum thickness of insulation was determined for five fuel types including coal, natural gas, fuel oil, LPG and electricity. The C_f, H_u values of fuels and η_s are given in Table 2.

Also, economic analysis was conducted by LCCA. The parameters used in calculation process are given in Table 3.

Table 2. Prices, lower heating values and efficiencies of heating systems

Fuel	H_u	n_s	C_f
N. gas	34518000 J m^{-3}	0.90	0.313 \$ m^{-3}
Coal	21112500 J kg^{-1}	0.65	0.196 \$ kg^{-1}
Fuel-oil	41317000 J kg^{-1}	0.80	0.737 \$ kg^{-1}
LPG	46442400 J kg^{-1}	0.88	1.752 \$ kg^{-1}
Elect.	3598240 J kWh^{-1}	0.99	0.119 \$ kWh^{-1}

Table 3. Parameters used in calculation

Parameter	Value
Heating and cooling degree days	See Table 1
Fuel	See Table 2
Insulation	
Rock wool	
Conductivity, *k*	0.040 W m K^{-1}
Cost, C_I	80 \$ m^{-3}
Glass wool	
Conductivity, *k*	0.032 W m K^{-1}
Cost, C_I	75 \$ m^{-3}
External wall	
2 cm internal plaster (lime-based)	0.087 W m K^{-1}
19 cm brick	0.450 W m K^{-1}
3 cm external plaster(cement-based)	1.400 W m K^{-1}
R_{wt}	0.625 m^2 K W^{-1}

3. Results and Discussions

Thermal insulation plays a key role in energy management applications. Since the insulation system is so vital for energy conservation, the proper selection of this system is of great importance (Lucas and Ferreira, 2010). By determining the proper insulation thickness, the economic trade-offs between insulation costs and energy savings are considered.

Figure 2 presents the impact of insulation thickness on the total cost over the lifetime of 20 years with GW insulation material in Ankara. The figure demonstrates that the total cost curve is at minimum the optimal insulation thickness.

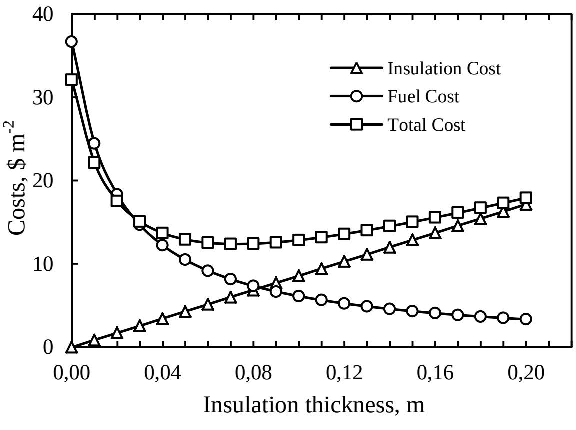

Figure 2. Effect of insulation thickness on the total cost for Ankara

The optimum insulation thickness for the other cities are calculated and shown in Figure 3. The insulation thickness reaches peak values due to harsh climate conditions and higher fuel expenses for both insulation materials, as expected (Çetintaş and Yılmaz, 2018).

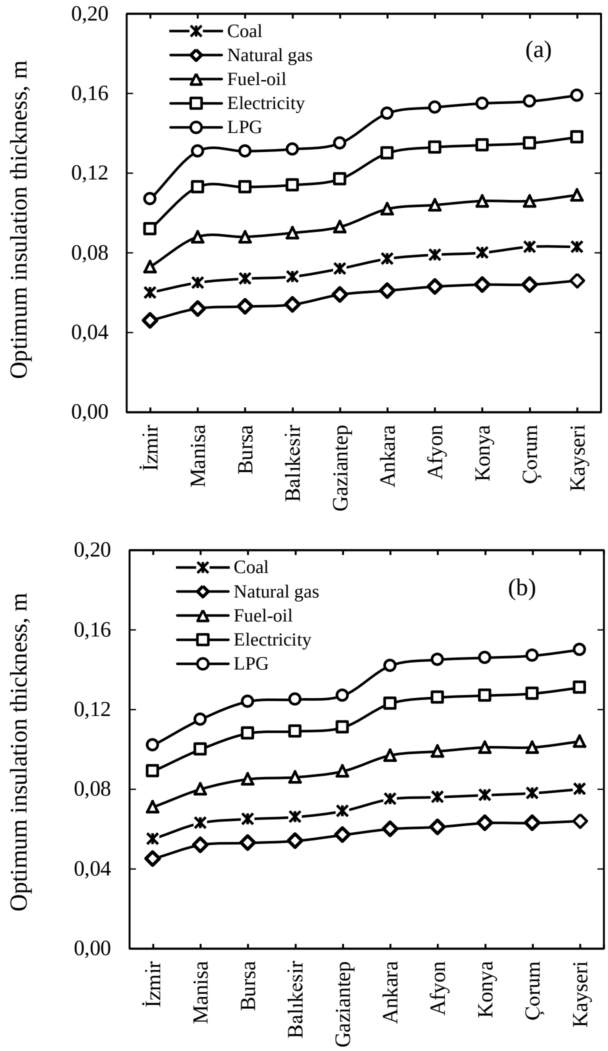

Figure 3. Optimum insulation thickness for (a) RW and (b) GW in selected cities

The percentages of energy savings were calculated as the costs difference between the cost of both heating and cooling insulated and uninsulated cases. The variations of energy savings versus selected cities with respect to the fuel types are shown in Figure 4. Increasing the fuel costs raises the net energy savings. The greatest energy savings for the ten cities is achieved using LPG, followed by electricity, fuel-oil, coal, and natural gas. As mentioned by Kurekci (2016), the ranking would change depending on variation in fuel prices. Also, energy savings increases with severe climatic conditions. Thus, energy savings are more important for colder climate conditions and higher fuel prices (Aktemur, 2018). When compared to the two insulation materials used in this study, energy savings take higher values with GW insulation.

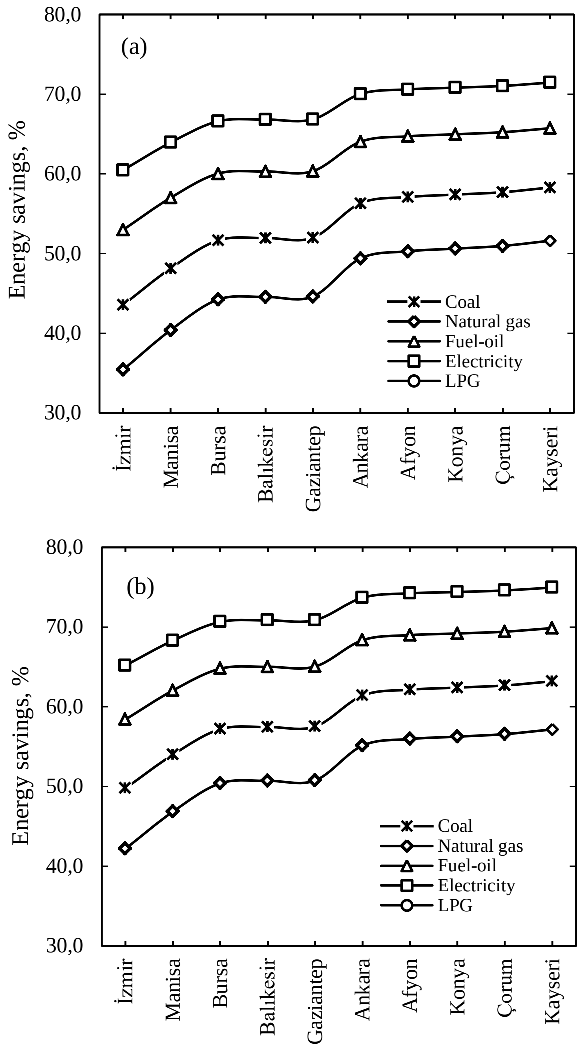

Figure 4. Energy savings (%) for (a) RW and (b) GW in selected cities

The emissions of CO_2 are presented in Table 4 for without insulation (WI), and optimum thicknesses of RW and GW. It is observed that the highest emission of CO_2 is reached with coal and the emission of CO_2 decreases by the use of insulation materials (Figure 5). In addition, it can be seen that when the region is much colder, the reduction rate of CO_2 is larger. When total reduction of CO_2 discharges is investigated after insulation, the minimum reduction value (64.79%) appears in warmest zone (İzmir) with natural gas and RW insulation material, on the other hand, the coldest zone (Kayseri) has the maximum value (88.76%) with LPG and GW insulation materials. Thus, in order to decrease the CO_2 emission due to poultry production, insulation on the exterior walls in colder climates should be considered in Turkey. Similar results were reported in literature (Agra et al., 2011; Evin and Ucar, 2019; Gürel and Daşdemir, 2011; Yildiz et al., 2008).

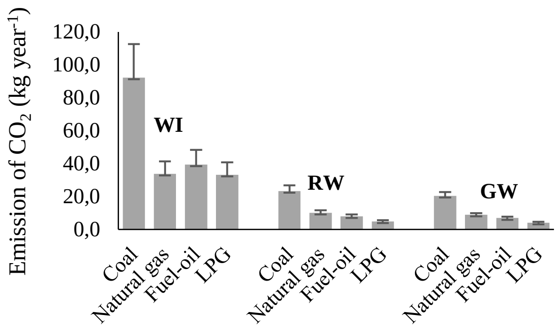

Figure 5. Emission of CO_2 for different fuels

Table 4. Emission of CO_2 (kg year^{-1}) obtained different cities and fuels for Without insulation (WI), Rock wool (RW) and Glass wool (GW) insulation materials

City	Coal			Natural gas			Fuel-oil			LPG		
	WI	RW	GW	WI	RW	GW	WI	RW	GW	WI	RW	GW
İzmir	55.9	16.5	16.2	20.5	7.2	7.2	24.0	6.1	5.5	20.2	3.8	3.3
Manisa	69.0	19.2	17.9	25.3	8.2	8.0	29.6	6.6	6.1	24.9	4.0	3.7
Bursa	81.7	22.2	19.5	30.0	9.6	8.6	35.0	7.8	6.6	29.5	4.7	4.0
Balıkesir	83.0	22.3	19.5	30.4	9.6	8.7	35.6	7.8	6.7	30.0	4.8	4.0
Gaziantep	83.1	22.4	19.8	30.5	9.7	8.7	35.7	7.8	6.7	30.1	4.8	4.0
Ankara	103.7	25.4	21.8	38.1	11.1	9.6	44.5	8.8	7.4	37.5	5.4	4.5
Afyon	108.3	26.0	22.1	39.7	11.3	9.8	46.4	9.0	7.6	39.1	5.5	4.5
Konya	110.1	26.2	22.5	40.4	11.3	9.9	47.2	9.0	7.6	39.8	5.5	4.6
Çorum	111.9	26.9	22.6	41.1	11.5	10.0	48.0	9.2	7.7	40.5	5.6	4.6
Kayseri	115.6	26.8	22.9	42.4	11.6	10.1	49.6	9.3	7.8	41.8	5.7	4.7

Table 5. Optimum insulation thickness at external walls of buildings both heating and cooling ($d_{opt,HC}$), energy savings (A_{HC}) and payback periods (PP_{HC}) for RW material

City	Coal			Natural gas			Fuel-oil			LPG			Electricity		
	$d_{opt,HC}$ (m)	A_{HC} (%)	PP_{HC} (year)	$d_{opt,HC}$ (m)	A_{HC} (%)	PP_{HC} (year)	$d_{opt,HC}$ (m)	A_{HC} (%)	PP_{HC} (year)	$d_{opt,HC}$ (m)	A_{HC} (%)	PP_{HC} (year)	$d_{opt,HC}$ (m)	A_{HC} (%)	PP_{HC} (year)
İzmir	0.060	43.55	1.68	0.046	35.42	2.00	0.073	52.98	1.34	0.107	64.60	0.96	0.092	60.48	1.09
Manisa	0.065	48.14	1.52	0.052	40.39	1.78	0.088	57.00	1.20	0.131	67.78	0.87	0.113	63.94	0.99
Bursa	0.067	51.65	1.39	0.053	44.23	1.66	0.088	60.04	1.11	0.131	70.16	0.80	0.113	66.60	0.91
Balıkesir	0.068	51.95	1.38	0.054	44.56	1.63	0.090	60.30	1.10	0.132	70.37	0.79	0.114	66.82	0.90
Gaziantep	0.072	51.99	1.36	0.059	44.61	1.63	0.093	60.34	1.10	0.135	70.40	0.79	0.117	66.85	0.90
Ankara	0.077	56.30	1.23	0.061	49.38	1.46	0.102	64.03	0.98	0.150	73.25	0.71	0.130	70.02	0.80
Afyon	0.079	57.09	1.20	0.063	50.28	1.44	0.104	64.71	0.96	0.153	73.78	0.70	0.133	70.60	0.78
Konya	0.080	57.40	1.19	0.064	50.62	1.43	0.106	64.97	0.95	0.155	73.98	0.69	0.134	70.82	0.78
Çorum	0.083	57.70	1.18	0.064	50.96	1.40	0.106	65.23	0.95	0.156	74.18	0.68	0.135	71.04	0.77
Kayseri	0.083	58.29	1.17	0.066	51.61	1.39	0.109	65.73	0.93	0.159	74.56	0.67	0.138	71.46	0.76

Table 6. Optimum insulation thickness at external walls of buildings both heating and cooling ($d_{opt,HC}$), energy savings (A_{HC}) and payback periods (PP_{HC}) for GW material

City	Coal			Natural gas			Fuel-oil			LPG			Electricity		
	$d_{opt,HC}$ (m)	A_{HC} (%)	PP_{HC} (year)	$d_{opt,HC}$ (m)	A_{HC} (%)	PP_{HC} (year)	$d_{opt,HC}$ (m)	A_{HC} (%)	PP_{HC} (year)	$d_{opt,HC}$ (m)	A_{HC} (%)	PP_{HC} (year)	$d_{opt,HC}$ (m)	A_{HC} (%)	PP_{HC} (year)
İzmir	0.055	49.76	1.47	0.045	42.17	1.72	0.071	58.41	1.19	0.102	68.87	0.87	0.089	65.18	0.98
Manisa	0.063	53.99	1.33	0.052	46.83	1.54	0.080	62.05	1.07	0.115	71.71	0.78	0.100	68.31	0.89
Bursa	0.065	57.19	1.23	0.053	50.40	1.45	0.085	64.79	0.99	0.124	73.82	0.72	0.108	70.65	0.82
Balıkesir	0.066	57.46	1.22	0.054	50.71	1.43	0.086	65.02	0.99	0.125	74.00	0.72	0.109	70.85	0.81
Gaziantep	0.069	57.52	1.21	0.057	50.75	1.42	0.089	65.05	0.98	0.127	74.03	0.72	0.111	70.88	0.81
Ankara	0.075	61.41	1.09	0.060	55.13	1.29	0.097	68.36	0.88	0.142	76.57	0.64	0.123	73.69	0.73
Afyon	0.076	62.15	1.07	0.061	55.96	1.27	0.099	68.99	0.87	0.145	77.06	0.63	0.126	74.24	0.72
Konya	0.077	62.41	1.06	0.063	56.26	1.26	0.101	69.20	0.86	0.146	77.21	0.63	0.127	74.41	0.71
Çorum	0.078	62.68	1.06	0.063	56.57	1.24	0.101	69.43	0.85	0.147	77.38	0.62	0.128	74.60	0.70
Kayseri	0.080	63.20	1.04	0.064	57.16	1.23	0.104	69.88	0.84	0.150	77.72	0.61	0.131	74.98	0.69

The optimum insulation thickness at chosen cities with calculated percentages of energy savings and pay back periods are given in Table 5 and 6. An analysis of these findings indicate that the optimum thickness of insulation for RW insulation material changes between 4.60 and 15.90 cm, energy savings change between 35.42% and 74.56%, and payback periods were between 0.67 and 2.00 years, while for GW material ranges between 4.50 and 15.00 cm, energy savings range between 42.17% and 77.72%, and payback periods were between 0.61 and 1.72 years depending on the city, and cost of fuel. Increase in thickness of insulation material reduced annual fuel consumption and thus decreased emissions from combustion of fuels (Evin and Ucar, 2019). Whenever energy savings increase, the payback period shortens, and highest values are observed in the warmest region. On the other side, in the cold regions, the payback period is short, but insulation cost is higher. As a result, GW seems to be more reasonable option than RW considering energy savings and payback periods.

4. Conclusions

Thermal insulation is one of the best ways to conserve energy. However, it is unacceptable to provide maximum energy conservation without considering the cost of selected insulation method. In this paper, optimum insulation thickness were determined by considering two different insulation materials and five types of fuel. Calculations were made for ten cities in Turkey with the highest number of laying hens, and the following conclusions have been drawn based on the calculations.

The highest value for optimum insulation thickness (15.90 cm) was attained in Kayseri with the LPG fuel type and RW insulation material, while the lowest optimum insulation thickness (4.50 cm) was obtained in İzmir with the natural gas fuel type and GW insulation material.

The maximum value in energy savings (77.72%) was reached in Kayseri with the LPG fuel type and GW insulation material.

CO_2 emissions had the lowest value (3.30 kg year^{-1}) in İzmir when the GW insulation material and LPG as an energy source was used. Given the total environmental impact, the most appropriate fuel is LPG and the most appropriate insulation material is GW.

The shortest payback period (0.61 year) was attained in Kayseri with the LPG fuel type and GW insulation material.

In this study, the RW and GW insulation materials, and only one sample wall structure variation were taken into consideration when calculating optimum insulation thickness. In future studies, optimum thickness values to be calculated taking into account various insulation materials and wall structures are expected to be the most appropriate value for practical use.

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