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RESEARCH ARTICLE

Determination of optimum insulation thicknesses using economical analyse for exterior walls of buildings with different masses

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ABSTRACT

In this study, five different cities were selected from the five climatic zones according to Turkish standard TS 825, and insulation thicknesses of exterior walls of sample buildings were calculated by using optimization. Vertical perforated bricks with density of 550 kg/m^3 and 1000 kg/m^{3}werechosen within the study content. Glass wool, expanded polystyrene (XPS), extruded polystyrene (EPS) were considered as insulation materials. Additionally, natural gas, coal, fuel oil and LPG were utilized as fuel for heating process while electricity was used for cooling. Life cycle cost (LCC) analysis and degree-day method were the approaches for optimum insulation thickness calculations. As a result, in case of usage vertical perforated bricks with density of 550 kg/m^3 and 1000 kg/m^3 resulted different values in between 0.005-0.007 m (5-7 mm) in the optimum insulation thickness calculations under different insulation materials. Minimum optimum insulation thickness was calculated in case XPS was preferred as insulation material, and the maximum one was calculated in case of using glass wool.

1. Introduction

Heat insulation is the most important pillar of the developed policies about the concept of energy efficiency all over the world. The fact that the housing and building sector in Turkey consumes about 30-35% of the total energy and has a great saving potency increased the interest in the sectoral manner [1].

In heat insulation applications, energy loss and air pollution can be reduced by increasing the thickness of insulation material. However, it may be neither economical nor practical to use increasingly large amounts of insulation so as to achieve energy savings. A balance should be established between the insulation investment and the savings to be provided from the insulated building. The best insulation thickness is considered as mentioned balance. The insulation thickness, which provides the minimum insulation and operating costs for a given economic lifetime is called the optimal insulation thickness [2].

When the studies existed in the literature were examined, the optimum insulation thickness was calculated for the exterior walls of the building. To realize it, fuels such as natural gas, coal, fuel-oil, LPG, electricity and a wide range of insulating materials are used. Optimization calculations are made using the degree-day method and lifecycle cost analysis (LCC) for heating, cooling and both heating and cooling of buildings [1,3-8]. On the other hand, in some studies, the degree-day method and the economic model of P1-P2 were used as the optimization method [9-14]. In the study of Ucar [15], the optimum insulation thickness was found using exergoeconomic analysis considering the condensation of the insulation in the outer walls. In four climate characteristics dominated in four cities of Turkey, optimum insulation thicknesses were performed. Polystyrene is considered as insulation and coal as fuel. Nyers et al. [16] analyzed the optimum energy-economical thickness of the thermal insulation layers for the exterior walls of the building. The economic model is composed of energy and economic sections. The economic part of the model includes algebraic equations, investment, savings and usage periods. In the study of Kaynakli [17], heating and cooling degree-days, building life, inflation and interest rate, insulation material price, fuel price, external wall resistance, thermal conductivity value of insulating

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material, heating and cooling system efficiencies and solar radiation parameters were examined for optimum insulation thickness.

The purpose of this study is to calculate the insulation thicknessesby using optimization in the outer walls of sample buildings with different mass for five different cities in five climatic zones according to Turkish Standard TS 825. For different mass, vertical perforated brick with a thermal conductivity value of 0.32 W/m.K with a density of 550 kg/m^3, and a thermal conductivity value of 0.45 W/m.K with a density of 1000 kg/m^3 are considered. Optimum insulation thickness is the value that makes the total costs minimum for heating, cooling and heating+cooling. Glass wool, expanded polystyrene (XPS), extruded polystyrene (EPS) are considered as insulation materials. Also natural gas, coal, fuel oil, LPG are used as fuel for heating process while electricity is used for cooling. Lifecycle cost (LCC) analysis and degree-day method are used for optimum insulation thickness calculations. For optimum insulation thickness calculations, only heating case, only cooling case and both heatingplus cooling cases are considered.

2. Material and method

2.1. Total cost for heating, cooling and heating + cooling

Heat loss per unit area of the exterior wall of a building is computed as follows:

$$q = U(T_i - T_d) \tag{1}$$

Annual heat loss per unit area based upon degree-day concept is computed by the following equation.

$$q = 86400.DD.U \tag{2}$$

The total heat transfer coefficient for the wall is given by Equation 3, while the total thermal resistance for the uninsulated wall is determined according to Rt, w and the total heat transfer coefficient of the wall is obtained through Equation 4.

$$U = \frac{1}{\left(R_i + R_w + (x/k) + R_d\right)} \tag{3}$$

$$U = \frac{1}{\left(R_{t,w} + (x/k)\right)} \tag{4}$$

Here, Ri and Ro are internal and external thermal resistances. x is the insulation thickness. k is the thermal conductivity coefficient of the insulation material.

Heating fuel cost is computed as follows:

$$C_{A,H} = \left(\frac{86400.PWF.C_f.HDD}{(R_{t,w} + x/k).H_u.\eta}\right) \tag{5}$$

Total heating cost; the addition of insulation cost and the cost of fuel is:

$$C_{t,H} = \left(\frac{86400.PWF.C_f.HDD}{(R_{t,w} + x/k).H_u.\eta}\right) + \left(C_{ins}.x\right) \tag{6}$$

If the derivation of the total heating cost equations (insulation thickness) x is equal to zero, the optimum insulation thickness equation is obtained for the heating given below.

$$x_{opt,,H} = 293.94.\left(\frac{HDD.C_f.k.PWF}{H_u.C_{ins}.\eta}\right)^{1/2} - k.R_{t,w} \tag{7}$$

Cooling fuel cost is:

$$C_{A,C} = \left(\frac{86400.PWF.C_e.CDD}{(R_{t,w} + x/k).COP}\right) \tag{8}$$

Total cooling cost; the addition of insulation cost and the fuel cost is:

$$C_{t,C} = \left(\frac{86400.PWF.C_e.CDD}{(R_{t,w} + x/k).COP}\right) + \left(C_{ins}.x\right) \tag{9}$$

If the derivative of total cooling cost equations (insulation thickness) x is equal to zero, the optimum insulation thickness equation for cooling given below is obtained.

$$x_{opt,C} = 293.94.\left(\frac{CDD.C_e.k.PWF}{C_{ins}.COP}\right)^{1/2} - k.R_{t,w} \tag{10}$$

The total fuel cost for heating + cooling is the sum of heating and cooling fuel costs:

$$C_{A,H,C} = \left(\frac{86400.PWF.C_f.HDD}{(R_{t,w} + x/k).H_u.\eta} + \frac{86400.PWF.C_e.CDD}{(R_{t,w} + x/k).COP}\right) \tag{11}$$

Total cost is the sum of heating and cooling costs and insulation cost.

$$C_{t,H,C} = \left(\frac{86400.PWF.C_f.HDD}{(R_{t,w} + x/k).H_u.\eta} + \frac{86400.PWF.C_e.CDD}{(R_{t,w} + x/k).COP} \right) + (C_{ins}.x) \quad (12)$$

$$x_{opt,H,C} = 293.94.\left(\frac{HDD.C_f.k.PWF}{H_u.C_{ins}.\eta} + \frac{CDD.C_e.k.PWF}{C_{ins}.COP} \right)^{1/2} - k.R_{t,w} \quad (13)$$

If the derivative of the total cost equation (insulation thickness) x is equal to zero, the optimum insulation thickness equation is obtained for heating pluscooling that is given below [1,3,7,10,12,13,17,18].

Here, H_u is the lower temperature value, η is heating system efficiency, COP is cooling performance value, k is insulation material heat conductivity coefficient, C_f is fuel price, C_e is electricity price, C_{ins} is insulation material price, HDD and CDD are heating and cooling degree-day values, respectively.

LCC analysis is performed for optimum insulation thickness calculation.The total heating cost is evaluated by the present worth factor (PWF) for the N year lifetime [8]. The present worth factor is calculated as follows [8,19];

$$PWF = \frac{(1+r)^N - 1}{r.(1+r)^N} \quad (14)$$

If i> g; then the actual interest rate is,

$$r = \frac{i-g}{1+g} \quad (15)$$

If i<g then;

$$r = \frac{g-i}{1+i} \quad (16)$$

If i=g then;

$$PWF = \frac{N}{1+i} \quad (17)$$

2.2. Values used in calculations

The outer wall structures and heat transfer coefficients are given in Table 1. Table 2 shows heating and cooling degree-day values for cities in five different climatic regions. The basic temperature was selected to be 19.5 ^{0}C for heating and 22 ^{0}C for cooling.Table 3 shows fuels used for heating. The electricity price and cooling performance value (COP) value used for cooling are shown in Table 4. The insulation materials and properties used on the outer walls were given in Table 5. In addition, financial values including inflation and interest rates were given in Table 6.

Table 1. External wall building components andheat conduction coefficients [18].

Thickness	Component	Value
	R_i (Internal film thermal resistance)	0.130 m^2.K/W
0.030 m	Lime mortar-cement mortar internal plaster	1.000 W/m.K
0.190 m	Vertical Perforated Brick	0.32 ve 0.45 W/m.K
x m	Insulation	k_{ins} W/m.K
0.030 m	Cement mortar outer plaster	1.600 W/m.K
	R_d (External film thermal resistance)	0.040 m^2.K/W

In the study, the effect of using bricks of different density on the insulation thickness was investigated. In addition, it is suggested that heating and cooling periods should be considered together while insulating buildings are prevealing for hot climate zones.

Table 2. Heating and Cooling Degree-days for different climate zones in cities [20].

Climate Zones	City	Heating Degree-days	Cooling Degree-days	Latitude	Longitude	Elevation (m)
1	İzmir	1480	617	38.43	27.17	28.55
2	Balıkesir	2312	369	39.65	27.87	147.00
3	Konya	3162	275	37.87	32.48	1028.59
4	Sivas	3643	171	39.75	37.02	1285.00
5	Kars	4770	96	40.62	43.10	1775.00

Table 3. Fuels and properties[21].

Fuel	Price	Lower thermal value (H_u)	Heating system efficiency(η_s)
Natural Gas	0.3601 $/m^3	34.526 10^6J/m^3	0.93
Coal	0.2216 $/kg	29.295 10^6J/kg	0.65
Fuel-oil	0.7340 $/kg	40.594 10^6J/kg	0.80
LPG	1.6411 $/kg	46.453 10^6J/kg	0.90

Table 4. Electricity price and cooling COP [9,22].

Parameter	Value
Price	0.174 $/kWh
Cooling COP	2.5

Table 5. Insulation materials and properties [3].

Insulation Materials	k (W/m.K)	C_{ins} ($/m^3)
Glass wool	0.040	75
Expanded polystyrene (EPS)	0.039	120
Ekstrüde polystyrene (XPS)	0.031	180

Table 6. Financial values [3].

Financial Values	Value
Interest rate, (i)	% 8.25
Inflation rate, (g)	% 7.91
Lifecycle time, N	10 yıl
PWF	9.83

3. Results

In Figure 1, cost curves of optimum insulation thickness for a) heating period b) cooling period c) heating plus cooling period for Izmir city in case of vertical perforated brick with density of 550 kg/m^3 and thermal conductivity of 0.32 W/m.K, glass wool as insulation material and natural gas as fuel usage. Figure 2 shows the results of cost curves for optimum insulation thickness a) heating period b) cooling period c) heating plus cooling period for Kars city in case of vertical perforated brick with density of 1000 kg/m^3 and thermal conductivity of 0.45 W/m.K, XPS as insulation material, and coal as fuel usage. Table 7 shows the optimum insulation thickness because of various fuel and insulation materials usage for vertical perforated brick with 550 kg/m^3 density and 0.32 W/m.K heat conduction in the heating period. Table 8 represents the optimum insulation thickness due to various fuel and insulation materials usage for vertical perforated brick with 1000 kg/m^3 density and 0.45 W/m.K heat conduction in the heating period. In Table 9, the optimum insulation thickness due to various fuel and insulation materials usage for vertical perforated brick with 550 kg/m^3 density and 0.32 W/m.K heat conduction in the cooling period. In Table 10, the optimum insulation thickness due to various fuel and insulation materials usage for vertical perforated brick with 1000 kg/m^3 density and 0.45 W/m.K heat conduction in the cooling period. Table 11 shows the optimum insulation thickness due to various fuel and insulation materials usage for vertical perforated brick with 550 kg/m^3 density and 0.32

W/m.K heat conduction in the heating+cooling period. Table 12 represents the optimum insulation thickness due to various fuel and insulation materials usage for vertical perforated brick with 1000 kg/m^3 density and 0.45 W/m.K heat conduction in the heating+cooling period.

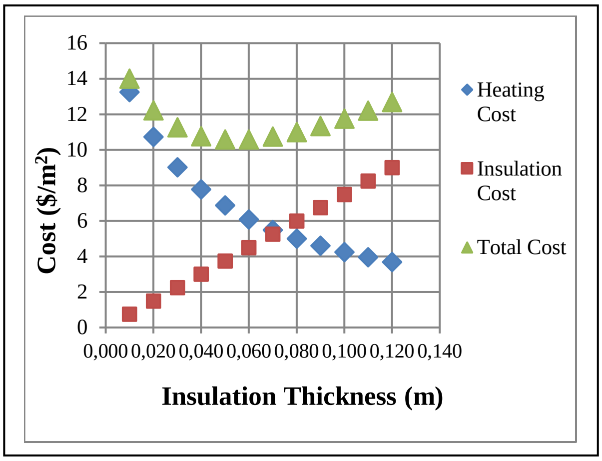
4. Discussion

During the heating period, in case of vertical perforated brick with a density of 550 kg/m^3 usage, the optimum insulation thickness range in different fuel and insulation materials are as follows; 0.024-0.130 m in Izmir, 0.036-0.170 m in Balıkesir, 0.047-0.221 m in Konya, 0.052-0.222 m in Sivas, and 0.063-0.259 m in Kars. On the other hand, these results during the cooling period are; 0.017-0.041 m in Izmir, 0.000-0.024 m in Balıkesir, 0.000-0.017 m Konya, while it was found that the optimum economic choice for Sivas and Kars was not to use insulation Besides, in the heating plus cooling period; results are found to be 0.039-0.146 m in Izmir, 0.044-0.178 m observed in Balıkesir, 0.052-0.226 m observed in Konya, 0.055-0.225 m in Sivas and 0.065-0.260 m observed in Kars.

During the cooling period, in case of vertical perforated brick with a density of 1000 kg/m^3 usage, the optimum insulation thickness range in different fuel and insulation materials are as follows; 0.029-0.136 m in Izmir , 0.042-0.177 m in Balıkesir, 0.052-0.228 m in Konya, 0.057-0.229 m in Sivas , 0.069 -0.266 m in Kars. In the cooling period, 0.022-0.048 m in Izmir, 0.012-0.031 m in Balıkesir, 0.000-0.023 m in Konya and 0.000-0.013 m in Sivas and It was found that the optimum economic choice for Kars was not to use insulation. And finally, in the heating + cooling period, 0.044-0.152 m in Izmir, 0.050-0.185 m in Balıkesir, 0.057-0.233 m in Konya, 0.061-0.232 m in Sivas and 0.070-0.267 m in Kars.

When vertical hole bricks are used in the external walls of the example building at 550 kg/m^3 and 1000 kg/m^3 density, the lower optimum thickness of insulation is calculated at the low density brick refering 550 kg/m^3 for all provinces.

In the literature studies, bricks of different density are used. In general, high-density bricks are used. This affects the insulation thickness. As shown in this study, when using low density bricks, the insulation thickness is lower. This is also very important factor in terms of cost and additional workmanship.



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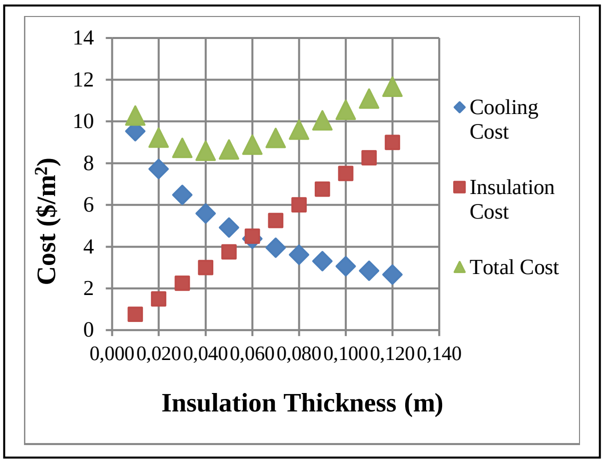

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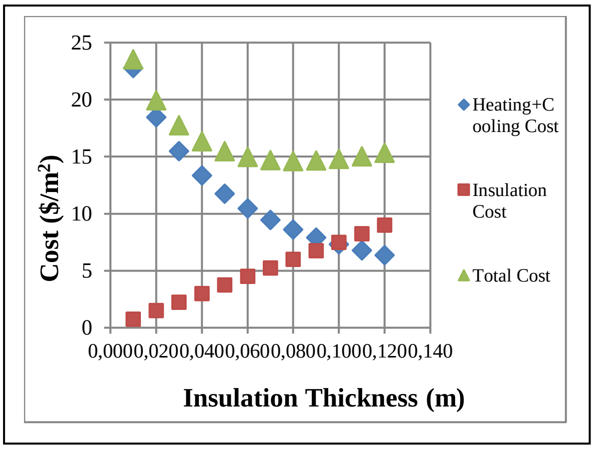
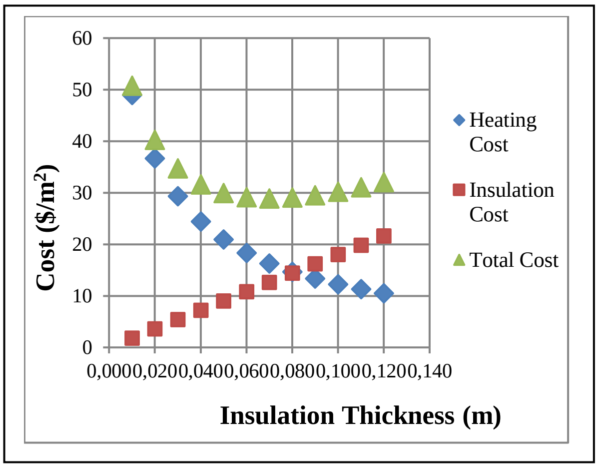
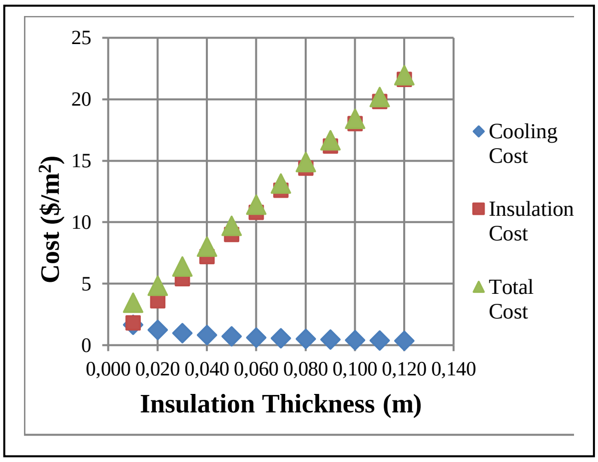


(c)

Figure 1. Cost curves of optimum insulation thickness for (a) heating period (b) cooling period (c) heating + cooling period for Izmir city in case of vertical perforated brick with density of 550 kg/m^3 and thermal conductivity of 0.32 W/m.K, glass wool as insulation material and natural gas as fuel usage.



(a)



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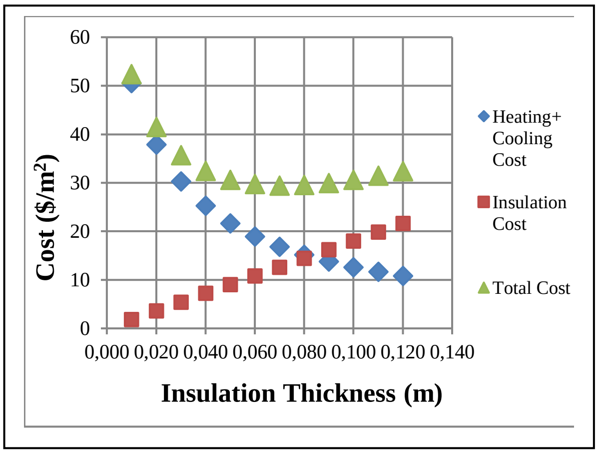

(c)

Figure 2. shows the results of cost curves for optimum insulation thickness (a) heating period (b) cooling period (c) heating + cooling period for Kars city in case of vertical perforated brick with density of 1000 kg/m^3 and thermal conductivity of 0.45 W/m.K, XPS as insulation material, and coal as fuel usage.

Table 7. Optimum insulation thickness due to various fuel and insulation materials usage for vertical perforated brick with 550 kg/m^3 density and 0.32 W/m.K heat conduction in the heating period(m)

City	Fuel											
	Natural Gas			Coal			Fuel-oil			LPG		
	Glass wool	EPS	XPS	Glass wool	EPS	XPS	Glass wool	EPS	XPS	Glass wool	EPS	XPS
İzmir	0.054	0.036	0.024	0.056	0.037	0.025	0.091	0.064	0.045	0.130	0.095	0.067
Balıkesir	0.076	0.053	0.036	0.078	0.054	0.038	0.121	0.088	0.062	0.170	0.127	0.090
Konya	0.094	0.067	0.047	0.097	0.069	0.048	0.147	0.109	0.077	0.221	0.166	0.119
Sivas	0.104	0.075	0.052	0.106	0.076	0.053	0.161	0.119	0.085	0.222	0.167	0.119
Kars	0.123	0.090	0.063	0.126	0.092	0.065	0.188	0.141	0.100	0.259	0.196	0.140

Table 8. Optimum insulation thickness due to various fuel and insulation materials usage for vertical perforated brick with 1000 kg/m^3 density and 0.45 W/m.K heat conduction in the heating period (m)

City	Fuel											
	Natural Gas			Coal			Fuel-oil			LPG		
	Glass wool	EPS	XPS	Glass wool	EPS	XPS	Glass wool	EPS	XPS	Glass wool	EPS	XPS
İzmir	0.061	0.043	0.029	0.063	0.044	0.030	0.097	0.071	0.050	0.136	0.102	0.072
Balıkesir	0.083	0.060	0.042	0.085	0.062	0.043	0.128	0.095	0.067	0.177	0.133	0.095
Konya	0.101	0.074	0.052	0.103	0.076	0.053	0.154	0.115	0.082	0.228	0.173	0.124
Sivas	0.110	0.081	0.057	0.113	0.083	0.059	0.168	0.126	0.090	0.229	0.174	0.125
Kars	0.130	0.097	0.069	0.133	0.099	0.070	0.195	0.148	0.106	0.266	0.202	0.146

Table 9. Optimum insulation thickness due to electric and insulation materials usage for vertical perforated brick with 550 kg/m^3 density and 0.32 W/m.K heat conduction in the cooling period (m)

City	Glass wool	EPS	XPS
İzmir	0.041	0.026	0.017
Balıkesir	0.024	0.013	---
Konya	0.017	---	---
Sivas	---	---	---
Kars	---	---	---

Table 10. optimum insulation thickness due to electric and insulation materials usage for vertical perforated brick with 1000 kg/m^3 density and 0.45 W/m.K heat conduction in the cooling period (m)

City	Glass wool	EPS	XPS
İzmir	0.048	0.032	0.022
Balıkesir	0.031	0.019	0.012
Konya	0.023	0.013	---
Sivas	0.013	---	---
Kars	---	---	---

Table 11. Optimum iınsulation thickness due to various fuel and insulation materials usage for vertical perforated brick with 550 kg/m^3 density and 0.32 W/m.K heat conduction in the heating+cooling period (m)

City	Fuel											
	Natural Gas+Electricity			Coal+Electricity			Fuel-oil+Electricity			LPG+Electricity		
	Glass wool	EPS	XPS	Glass wool	EPS	XPS	Glass wool	EPS	XPS	Glass wool	EPS	XPS
İzmir	0.081	0.057	0.039	0.082	0.058	0.040	0.111	0.080	0.056	0.146	0.107	0.076
Balıkesir	0.090	0.064	0.044	0.092	0.065	0.045	0.131	0.096	0.068	0.178	0.133	0.094
Konya	0.103	0.074	0.052	0.106	0.076	0.053	0.153	0.114	0.081	0.226	0.170	0.122
Sivas	0.109	0.078	0.055	0.111	0.081	0.057	0.164	0.122	0.087	0.225	0.169	0.121
Kars	0.126	0.092	0.065	0.129	0.094	0.066	0.190	0.142	0.101	0.260	0.197	0.141

Table 12. Optimum insulation thickness due to various fuel and insulation materials usage for vertical perforated brick with 1000 kg/m^3 density and 0.45 W/m.K heat conduction in the heating+cooling period (m)

City	Fuel											
	Natural Gas+Electricity			Coal+Electricity			Fuel-oil+Electricity			LPG+Electricity		
	Glass wool	EPS	XPS	Glass wool	EPS	XPS	Glass wool	EPS	XPS	Glass wool	EPS	XPS
İzmir	0.084	0.064	0.044	0.089	0.065	0.045	0.118	0.086	0.062	0.152	0.114	0.081
Balıkesir	0.097	0.071	0.050	0.099	0.072	0.051	0.138	0.103	0.073	0.185	0.139	0.100
Konya	0.110	0.081	0.057	0.112	0.083	0.059	0.161	0.121	0.086	0.233	0.177	0.127
Sivas	0.116	0.085	0.061	0.118	0.087	0.062	0.171	0.129	0.092	0.232	0.176	0.126
Kars	0.133	0.099	0.070	0.136	0.101	0.072	0.197	0.149	0.107	0.267	0.203	0.147

In addition, the heating and cooling period must be considered together for some provinces when insulation is applied. In particular, the cooling period should be taken into account as well as heating for hot climates such as the first and second region. In cold climates such as the fourth and fifth region, only the heating period can be considered. For some provinces, faults can only be made in the insulation application by considering the heating period.

5. Conclusion

Vertical perforated bricks with a density of 550 kg/m^3, a thermal conductivity of 0.32 W/m.K and vertical perforated bricks with a density of 1000 kg/m^3 with thermal conductivity of 0.45 W/m.K are used for optimum insulation thickness calculations for different insulation materials, and a difference ranging from 0.005 to 0.007 m (5-7 mm) is found. The optimum insulation thickness will be much larger in construction materials where the difference between the density and the thermal conductivity value is higher.

The minimum optimum insulation thickness is calculated when natural gas and XPS are used, while the maximum optimum insulation thickness is found when LPG and glass wool are used in the period of heating+cooling and heating. In the cooling period, the optimum insulation thickness was found in case of 550 kg/m^3 density vertical perforated brick usage Izmir, Balikesir and Konya. In the case of using 1000 kg/m^3 density vertical perforated brick, the optimum insulation thickness was found for the cities of Izmir, Balıkesir, Konya and Sivas. The highest optimum insulation thickness was obtained from glass wool and the lowest from XPS**.**

When utilizing low density bricks, the optimum insulation thickness is reduced. The labour cost increases when the density is increased. This also yields an increase in the cost of the building due to the use of additional materials and component. In addition, production of CO_2 and SO_2 emissions due to building components will increase. As a result, it is recommended to use low density bricks in terms of both cost and production carbon emission release.

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NOMENCLATURE

HDD	Heating degree-day	**Index**	
CDD	Cooling degree-day	ins	insulation
x	Insulation thickness (m)	H	heating
k	Insulation material heat conduction coefficient (W/m.K)	C	cooling
η	Heating system efficiency	f	fuel
H_u	Lower thermal value (J/m^3)	e	electricity
COP	Cooling performance coefficient	t,w	Uninsulated wall
C	Price ($)	f	fuel
XPS	Extruded polystyrene	t	total
EPS	Expanded polystyrene	t,H	Heating, total
PWF	Present Worth Factor	t,C	Cooling, total
i	Interest rate	w	Wall
g	Inflation rate	i	internal
R	Thermal resistance (m^2.K/W)	d	external
U	Heat transfer coefficient (W/m^2.K)		
T	Temperature (^{0}C)		

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